

# A TRIDENT SCHOLAR PROJECT REPORT

NO. 267

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**COPPER ELECTRODE DEGRADATION DUE TO THE  
RESISTANCE WELDING OF ALUMINUM**

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**UNITED STATES NAVAL ACADEMY  
ANNAPOLIS, MARYLAND**

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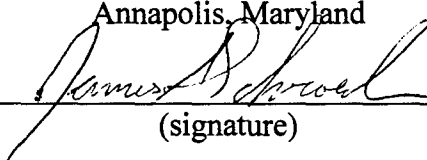
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**COPPER ELECTRODE DEGRADATION DUE TO THE  
RESISTANCE WELDING OF ALUMINUM**

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## ABSTRACT

This Trident research project focuses on increasing the life of copper electrodes used in the resistance welding of aluminum work pieces employed in the automotive and aerospace industries. When the copper and aluminum make contact at the interface, there is some undesirable mixing which results in the formation of a copper-aluminum eutectic phase. The welding temperature is high enough to melt the aluminum, but the eutectic phase has a lower melting temperature than either pure copper or pure aluminum. During subsequent welds the eutectic melts away, causing the copper to degrade rapidly and the electrode lifetime to be shortened.

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**Keywords:** resistance welding, electrode, eutectic, refractory metals, aluminum

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## 1.0 INTRODUCTION

Aluminum is widely used in automotive and aerospace industry and sections are commonly joined by resistance welding. Electrodes currently utilized degrade more rapidly during the welding of aluminum than during the welding of other metals, as measured by industry standards. It is believed that improvements in electrode lifetime may be linked to electrode composition. Research has been performed previously on the effects of the modification of welding parameters such as applied force, current, and electrode size and shape. The focus of this research was to investigate the impact of an electrode material composition alteration on weld performance for the resistance welding of aluminum. A change in the composition of the electrode was intended to raise the melting temperature of the electrode and impede the formation of a copper-aluminum eutectic phase at the electrode-work piece interface, which eventually leads to electrode degradation and poor weld performance. This paper discusses the fundamentals of the resistance welding process, the specifics of welding aluminum, and the effects of altering electrode composition on both the electrodes themselves and weld quality over time.

### 1.1 OBJECTIVES

The ultimate goal is to develop a resistance welding electrode for the welding of aluminum that has a lifetime greater than that of traditional electrodes. However, there are limitless parameter adjustments and weld tests that would be necessary in order to design a specific electrode with this capability that could function in all conditions. Consequently, achieving this goal would require significantly more time and resources. Therefore, this particular research included meeting the following interim objectives:

- a. Locate and identify formation of a copper-aluminum eutectic phase as a result of resistance welding using traditional copper electrodes.
- b. Manufacture electrodes suitable for welding using non-traditional processing techniques which are designed to distribute a refractory metal uniformly throughout the copper. Refractory additions in copper tend to segregate, so advanced processing methods are required to produce electrodes with refractory levels exceeding equilibrium solubility limits.
- c. Use electrode material loss and weld quality tests to indicate the potential impact on electrode lifetime of the new processing techniques.
- d. Provide recommendations for future testing and aluminum welding.

## 1.2 PROCEDURE

This project was divided into four steps: background research, processing, testing, and analysis. The background research investigated issues surrounding resistance welding, aluminum use and characteristics, and electrode development. Electrodes were produced during the processing step using several techniques. These techniques included laser cladding, plasma spraying, ion implanting, powder blending with Cold Isostatic Pressing (CIPing), mechanically alloying with CIPing, and spray forming. Each processing technique will be discussed in detail below. The two test methods utilized were (1) a study of material loss, measured by mass and overall length loss, of the electrode during welding and (2) a weld quality test as gauged by weld nugget diameter. The analysis consisted of comparing the electrodes with refractory alloy additions to a conventionally manufactured stock electrode. The comparison was completed using quantitative test results, optical microscopy, and scanning electron microscopy. The analysis focuses on the mixing of copper and aluminum at the electrode-work piece interface during welding and the composition and phases present in the electrodes before and after welding.

## 2.0 BACKGROUND

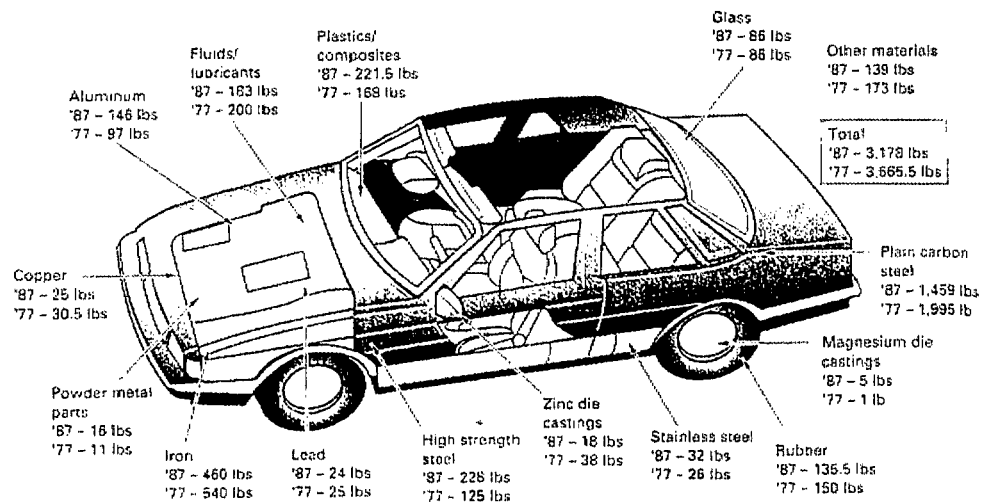
### 2.1 ALUMINUM ATTRIBUTES



**Figure 1. Solid Aluminum Frame** (from <http://www.alcoa.com/frame.asp?page=%2Fnews%2Fin dex%2Easp>)

Aluminum is desirable as a structural component for many reasons. It has good corrosion resistance, low density, and a high strength to weight ratio. Because of this, it is used to make both civilian and military automobiles, aircraft, missiles, and other vehicles lighter and more efficient while maintaining the required structural integrity. A vehicle made with aluminum components can weigh up to fifty percent less than one made entirely from steel. This is one of the reasons why Ferrari is building a new model with an all aluminum frame, as seen in Figure 1 [1]. Trends in the automotive industry are showing the

rapid increase of aluminum use, as seen in Figure 2 [2]. In the decade from 1977 to



**Figure 2. Automobile Composition Trends** (from *Materials and Processes in Manufacturing*, Eighth Edition, Copyright 1997, Prentice Hall, p. 228)

1987, the aluminum use in the typical automobile skyrocketed from 97 lbs. to 146 lbs. while the use of heavy plain carbon steel decreased. Overall, the same typical automobile decreased its total weight from 3,665.5 lbs. in 1977 to 3,178 lbs. in 1987. The lower weight contributes to increased fuel economy and more performance for the same power level. By using aluminum, the advantages of low weight can be achieved without having to suffer the consequences of small size [3].

## 2.2 RESISTANCE WELDING OVERVIEW

Resistance spot welding, as shown in Figure 3, is a spot welding application that utilizes the heat generated by electrical current passing through an area with high contact

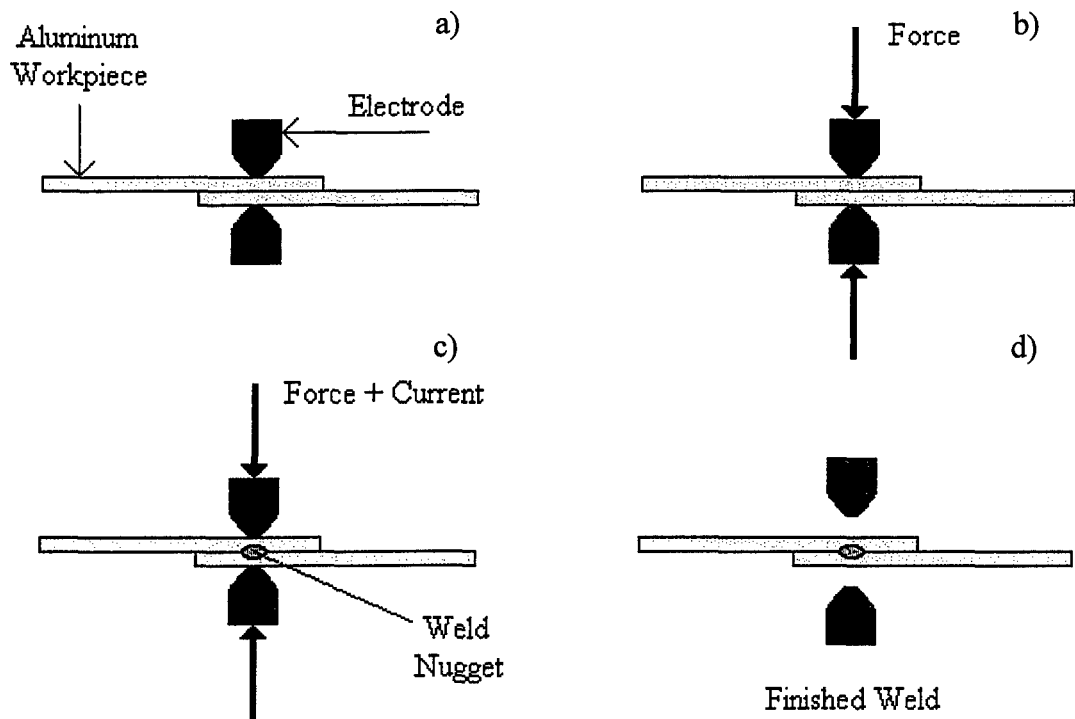
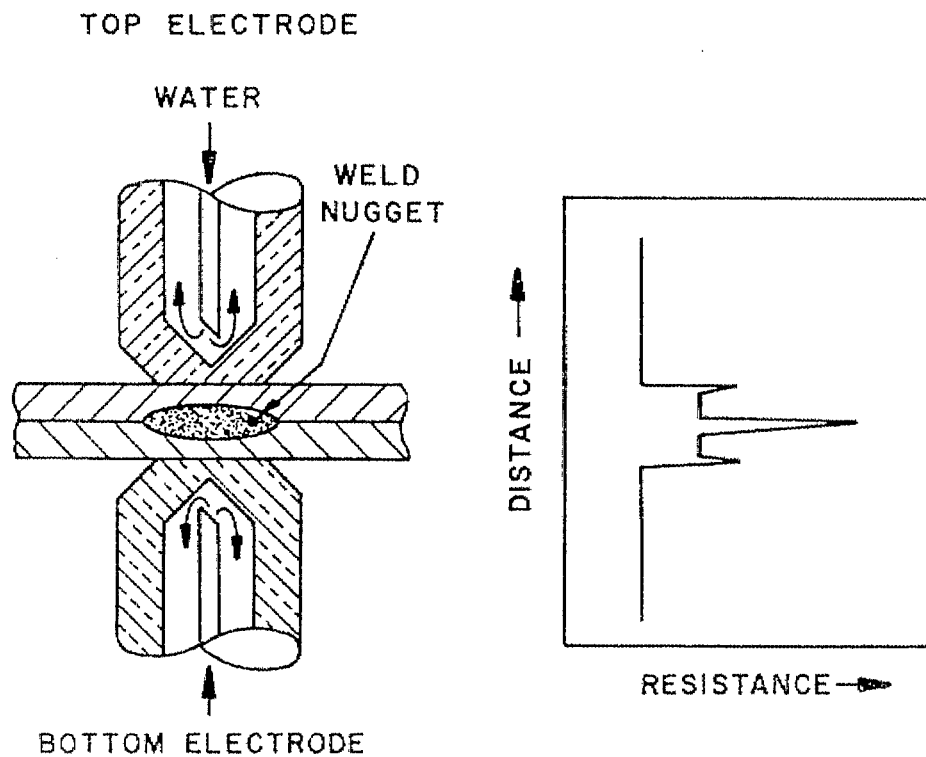


Figure 3. Resistance Welding Process

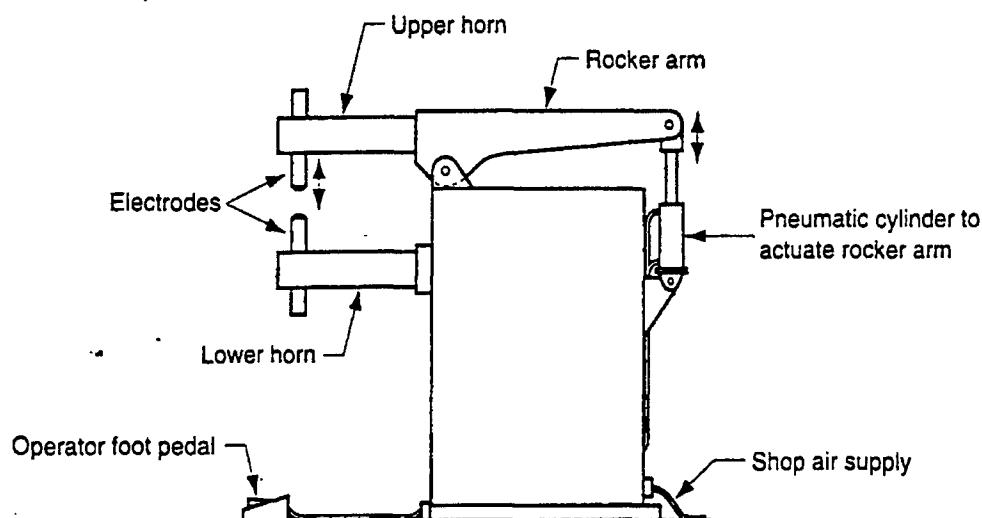
resistance to melt a work piece and create a weld nugget, joining the work piece. Figure 4 shows a qualitative representation of electrical resistance as a function of location. The current is conducted to the surface by two opposing electrodes that contact either side of the work piece. The electrode's function is to transfer a specified amount of current through the work piece while transmitting a constant force. In this capacity, they act as the link between the resistance welding machine and the work piece. A schematic of a resistance welding machine similar to the one used at the Ford Motor Company is shown in Figure 5 [4] and Figure 6 is a photograph of the actual welder used for



**Figure 4. Electrical Resistance Schematic (from *Welding in the Automotive Industry—State of the Art*, D.W. Dickenson, Copyright 1981, p. 115)**

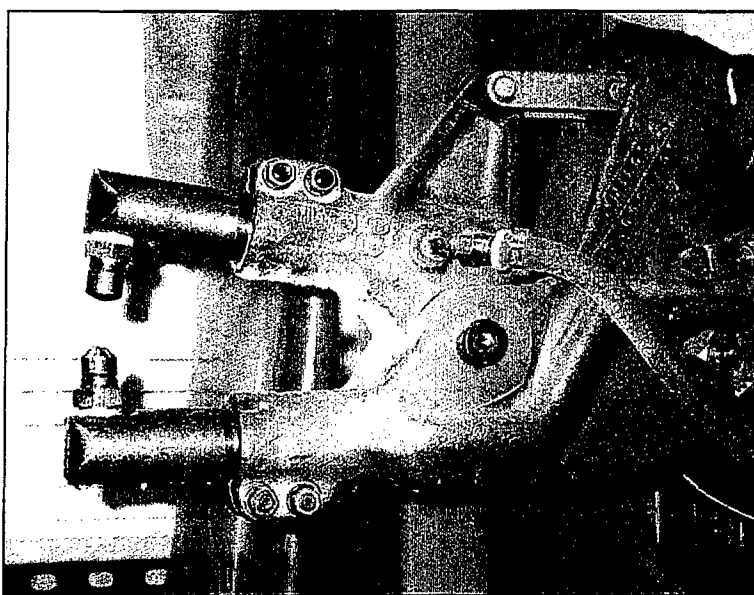
experimentation. The quality of the weld is highly dependent upon electrode properties and altering these properties significantly affects weld performance.





**Figure 5. Welding Equipment (from Fundamentals of Modern Manufacturing, M.P. Groover, Prentice Hall, Copyright 1996)**

There are several parameters that can be adjusted to give the proper weld nugget size based on the type of material being welded, the thickness, processing, and strength of weld required. Varying the magnitude of the current, applied force, weld time, and hold time, as well as altering the function that governs their application (i.e. ramp up vs. step



**Figure 6. Ford Resistance Welding Equipment**

up current application) change the characteristics and performance of the weld. The parameters were held constant for the duration of this research in an attempt to standardize the tests. The parameters used can be found in Table 1.

The important

measurements of weld effectiveness are weld

strength and surface deformation. Because it is difficult to test the strength of the weld in both tension and shear, the strength of the weld is gauged by peeling away one of the layers and measuring the minimum diameter

of the weld nugget that was formed. A peel test specimen diagramming a good weld, partial weld, and a no weld case is shown in Figure 7. The weld nugget on the left is clearly a good weld by its full and round appearance. The weld nugget in the middle is a partial weld and is approximately 25 percent of the full size weld nugget. It is considered a bad weld for this research, however, because the criterion for a nugget being considered a good weld is that it is greater than 70 percent of the average nugget size. The worst case, found in the weld on the right, produced almost no weld nugget. Finally, the depth of the surface deformation is often measured and reported as a percentage of work piece thickness as a representation of weld quality. For this research, surface appearance was not a concern, so the surface deformation was not measured. If a weld fails to meet



**Figure 7. Good, Partial, and No Weld**

minimum requirements during production, it could be a structural weak point. If there are too many bad welds in a finished product, it may not be functional or safe to use.

**Table 1. Weld Parameters Used**

Squeeze Time	30 Cycles
Weld Time	3 Cycles
Hold Time	20 Cycles
Weld Current	25 kAmps
Squeeze Pressure	4 Kpa

### 2.3 ALUMINUM RESISTANCE WELDING DIFFICULTIES

There are several difficulties associated with the resistance welding of aluminum. It has a much higher electrical and thermal conductivity than steel, as seen in Table 2,

**Table 2. Aluminum and Steel Properties (from Welding in the Automotive Industry—State of the Art, D.W. Dickenson, Copyright 1981, p. 114)**

Property	Steel	Aluminium
Specific gravity, kg/m <sup>3</sup>	$7.85 \times 10^3$	$2.7 \times 10^3$
Thermal conductivity, W/m°C	59	214
Specific heat, J/g°C	0.46	0.90
Coefficient of thermal expansion, °C <sup>-1</sup>	$1.3 \times 10^{-5}$	$2.4 \times 10^{-5}$
Latent heat of fusion, J/g	276	389
Melting point, °C	1528	660
Resistivity, Ωmm <sup>2</sup> /m	0.14	0.028

comparing selected properties of aluminum and steel. The specific heat and heat of fusion are high as well. Coupling these factors results in a required level of current three to five

times as high and a much shorter weld time as that required for steel. In other words, there is a high level of current required to weld the aluminum because of a high electrical

**Table 3. Typical Weld Parameters (from Welding in the Automotive Industry—State of the Art, D.W. Dickenson, Copyright 1981, p. 114)**

Material	Thickness		Electrode Force		Weld Time	Secondary Current
	mm	in.	kg	lb.	hertz	amperes
Aluminum	2.5	0.100	455	1000	14	44,000
Mild Steel	2.3	0.089	590	1300	24	16,000
HSLA Steel	2.3	0.089	750	1650	26	13,100

conductivity and the energy must be delivered rapidly before the heat is conducted away from the desired weld area because of the high thermal conductivity. What this means is that the aluminum has to be hit suddenly with a high level of current in order to produce a weld. The variation in weld parameters for typical aluminum and steel welding can be

found in Table 3. The aluminum welding has a much shorter weld time and about three times as much required current [5].

Another welding difficulty is that aluminum easily forms an alloy with copper. Since most spot welding electrodes are copper-based, this is a common problem. In fact, aluminum is occasionally deposited on the electrodes solely as a result of the electrode force, even with no current applied. This affinity leads to the rapid electrode degradation observed and eventually shortens electrode life [5].

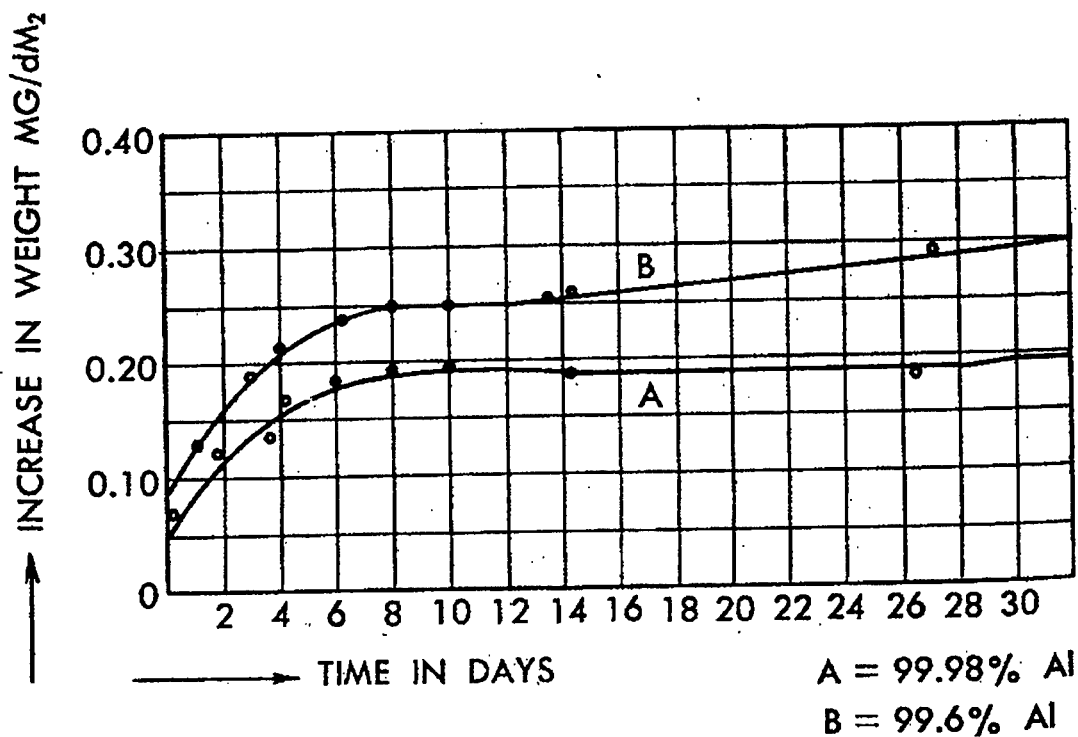


Figure 8. Aluminum Oxide Formation (from Welding Handbook, Volume Three, Seventh Edition, American Welding Society, Copyright 1980, p. 11-8)

Welding is also complicated by an oxide that forms rapidly on the surface of the aluminum. This phenomenon is seen in Figure 8, in a graph of milligrams per square decimeter vs. time in days, which shows full oxide formation in just 6 days. This makes obtaining a consistent current distribution nearly an impossibility due to the dynamic

contact resistance of the surface [6]. The variable thickness and microscopic topography of the oxide layer are a function of position and cannot be predicted or avoided. As a result, there is an uneven current distribution, and hot spots form at the electrode-work piece interface [7]. The oxide has a high electrical resistance and a high melting point of 2038 °C [3]. Through the resulting contact resistance, this contributes to the excessive heating at the electrode-work piece interface and leads to surface expulsion (melting and loss of aluminum at the surface) and faster copper-aluminum alloying, eventually degrading electrode performance. In order to combat the complications from the oxide layer, the surface of the work piece must be cleaned and welded within a period of 24 hours [7].

Oxide removal techniques from mill finished aluminum include chemical

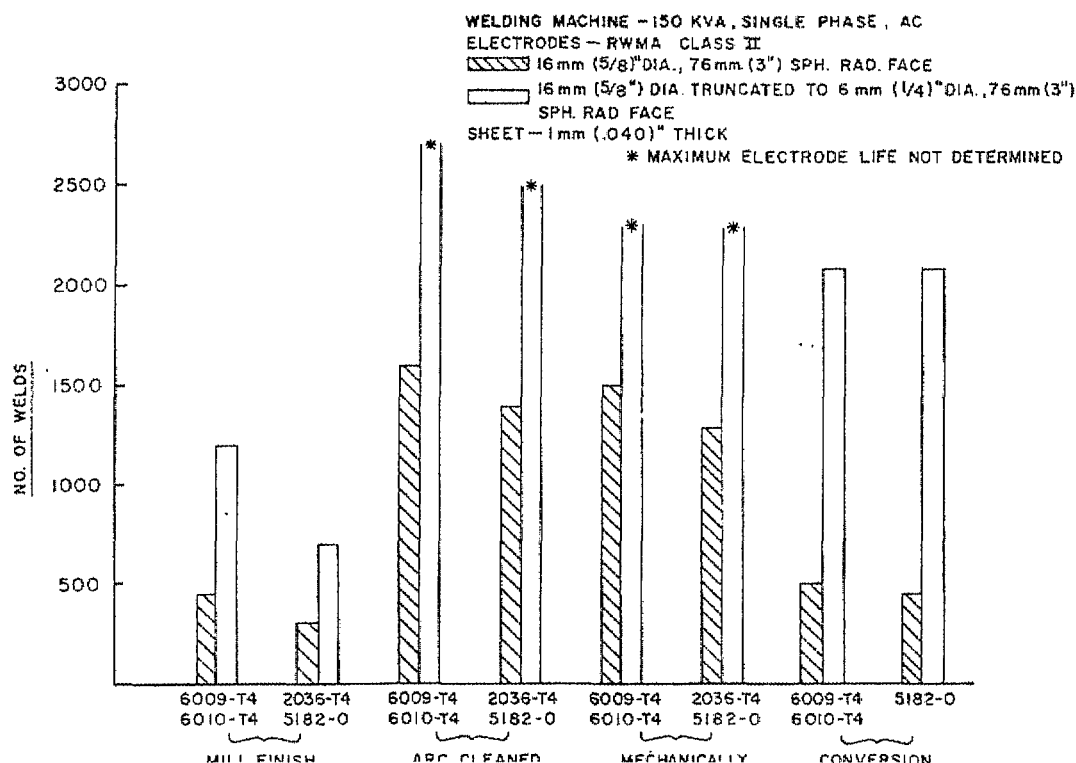
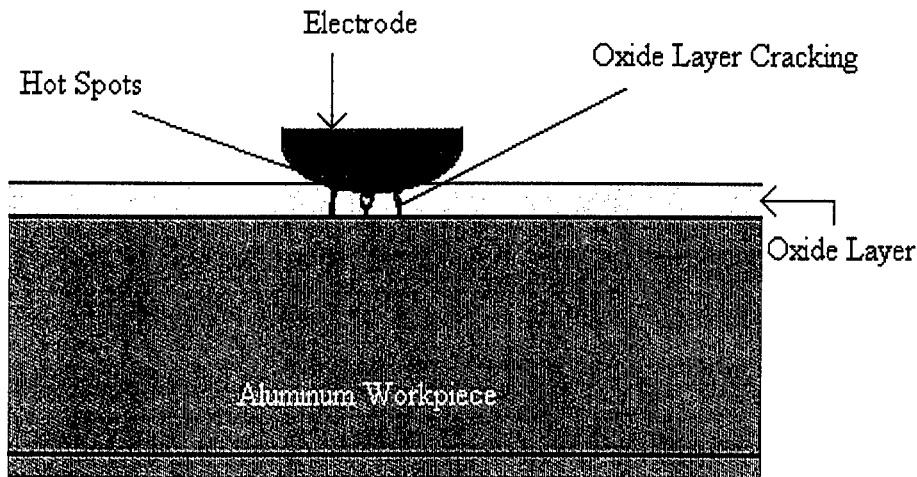


Figure 9. Cleaning Method Effectiveness (from Welding in the Automotive Industry—State of the Art, D.W. Dickenson, Copyright 1981, p. 311)

removal, mechanical removal, and arc removal. The effectiveness of these various cleaning methods on four different



**Figure 10. Oxide Layer Cracking**

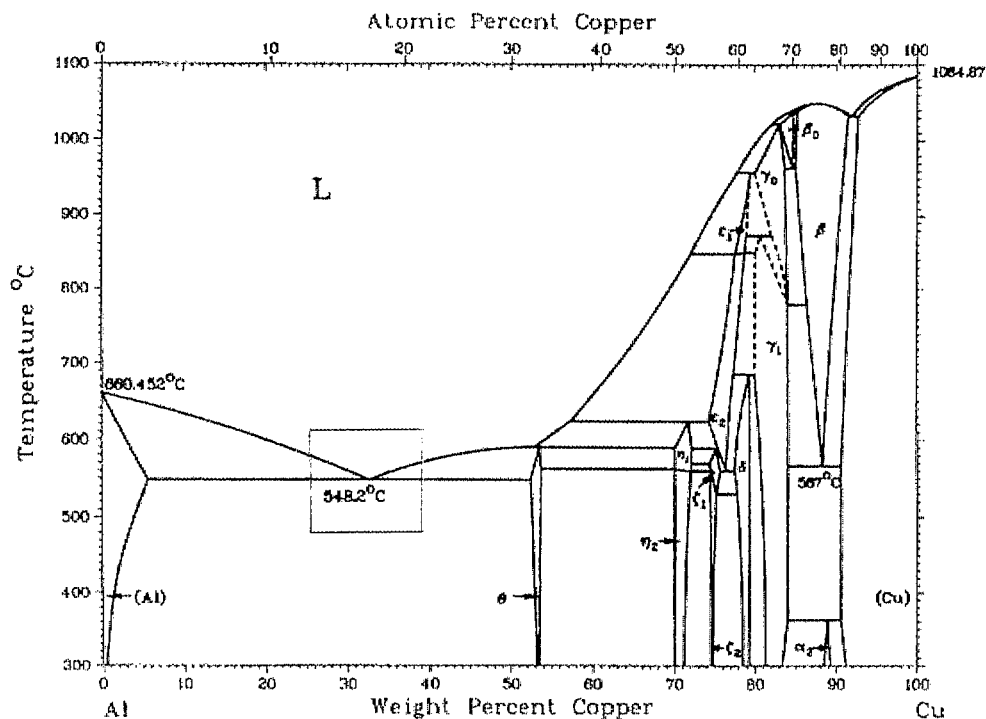
aluminum alloys is shown in Figure 9 [5]. These three methods have shown varying degrees of extended electrode life, but the benefits are not acquired without substantial additional cost or effort. Chemical removal of the oxide involves submersion of the work piece in a chemical cleaning solution. Although effective, this method is not practical for spot welding applications involving large or awkward aluminum work pieces. The abrasive removal of the oxide can be achieved with just a simple blasting, Scotch-Brite brushing, or wire brushing of the work piece [5]. This process has been found to be unacceptable to the automotive industry and other large



**Figure 11. Partially Degraded Electrode**

volume applications because of the extraordinary complications with adding an extra step

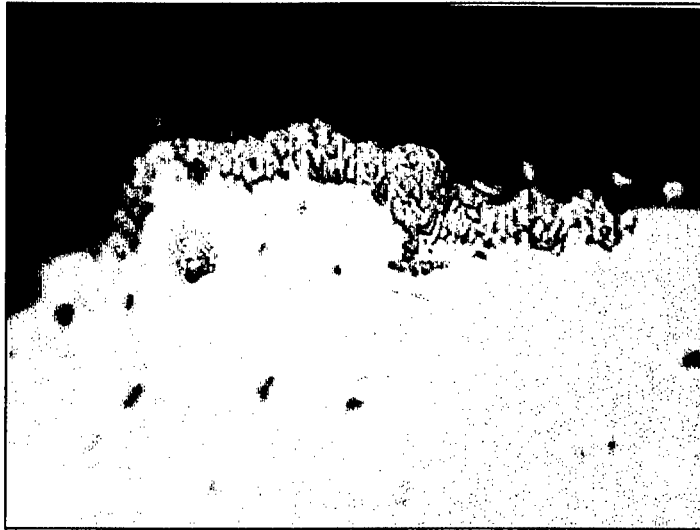
to the assembly line and the time lost to cleaning [8]. The third option is arc cleaning of the material immediately prior to welding. In this process, the spot welding electrodes are used to conduct an arc to the work piece before the force is applied to the electrodes. It is believed that the sputtering of the argon ions (present to shield gas surrounding the electrodes during arc welding) causes the cleaning. This method also adds considerable complications to the simplicity of spot welding due to extra required machinery and an additional power source for the arc [5]. Although better than welding raw material, these methods do not provide a complete solution because of substantial additional cost.



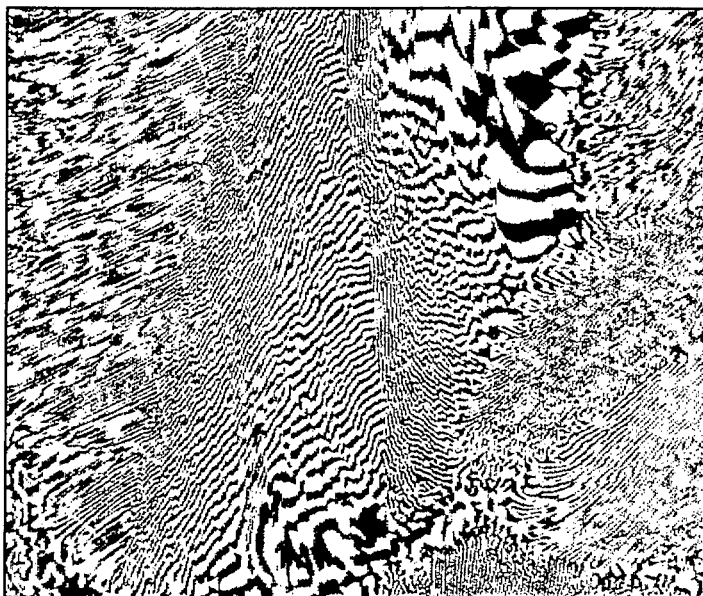
**Figure 12. Copper-Aluminum Phase Diagram (from Materials Science and Engineering Series, M. Hansen, McGraw Hill Book Company, Inc., Copyright 1958)**

Since the oxide forms rapidly and is difficult to remove sufficiently, the electrodes need to break through the oxide layer in almost all instances. When this

happens, small areas of low resistance are created in the otherwise highly resistive oxide. As a result, most of the current flows through very localized spots on the surface of the electrode and causes the formation of hot spots. This phenomenon is diagrammed in



**Figure 13a. Eutectic Optical Micrograph**



**Figure 13b. Textbook Eutectic Phase (from Metals Handbook, Volume 8, Eighth Edition, American Society for Metals, Copyright 1973, p. 16)**

Figure 10. As a result of the hot spots on the surface of the electrode, small amounts of both the electrode and the aluminum work piece melt at the interface during the weld. Due to the high solubility of the copper in

molten aluminum, the electrode is progressively degraded with each subsequent weld [9]. A picture of a partially degraded electrode is shown in Figure 11.

When using copper electrodes, surface melting results in the formation of a eutectic phase between the copper and aluminum, since the eutectic has the lowest melting point and is

formed preferentially at low temperatures [10]. A phase is a region of the microstructure



of a metal that has homogeneous characteristics and properties. A phase diagram is a map of all possible phases and is used to predict how elements mix at any specific composition and temperature. Each distinct region represents a different, unique phase. The eutectic phase forms at the lowest temperature on the top line, shown inside the red box in the copper-aluminum phase diagram in Figure 12 [11]. It is relatively easy to identify with optical microscopy due to its characteristic striped appearance, which is composed of layers of an aluminum rich  $\alpha$  phase and a  $\text{CuAl}_2$  intermetallic. A comparison of a eutectic found during this analysis with optical micrographs found in a reference text is shown in Figure 13. Figure 13a is an optical micrograph of the surface of a weld made with conventional electrodes on a conditioning plate after 22 welds. Figure 13b is a textbook example of  $\text{CuAl}_2$  eutectic formation [12]. Once melting occurs, the eutectic is formed and a small portion of the electrode is lost. As this process takes place, the surface topography of the electrode changes, as seen in Figure 7 earlier.

As a result, the electrode work piece interface characteristics are modified, which leads to a different current distribution and therefore different weld performance characteristics. This cycle is repeated for each weld performed and after just a few hundred welds, compared to several thousand for welding steel, the weld nugget fails to meet the minimum requirements and the electrodes must be discarded.

Resistance welding may be a preferred joining method for many applications because of its ease and versatility, but the factors discussed above make consistent aluminum resistance welding difficult to reproduce.

## 2.4 ELECTRODES

Electrodes are often mushroom shaped, as seen in Figure 14. They are fitted into the welding machine and held in place due to the friction created by the tapered shank after the electrode is seated, or pressed firmly into place. The shank is hollow to allow for a tube carrying cooling water to be inserted. They are often copper in color as this is typically the primary element.

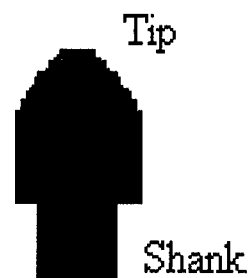


Figure 14. Electrode

The electrodes provide the interface between the current source and the work piece. As a result, electrode selection is one of the most important steps in resistance welding applications. There are three properties that are especially important to electrode selection that correspond to the three primary functions provided. The three properties are electrical conductivity for conducting current from the source to the work piece, hardness for transmitting the force to the work piece without excessive deformation, and thermal conductivity for dissipating heat from the weld zone following the weld [13]. In spot welding, the current, force and heat are concentrated in an extremely small contact area. This area can be subjected to current and force levels of up to 100,000 amperes and 100,000 psi, respectfully [14]. In order to compensate for this relatively harsh treatment of the electrodes, there are many different types of electrodes used for various applications. Variations include material composition changes and diversification of the processing techniques used to manufacture electrodes.

In order to be effective, an electrode must have a good balance of the three properties mentioned above. Electrical conductivity is important for obvious reasons, but

an electrode cannot be based on conductivity alone. An electrode with a very high electrical conductivity may not be able to withstand the necessary applied force at an elevated temperature. On the other hand, an electrode made from an extremely hard material that has low conductivity will not be able to deliver the required energy to produce a weld. Finally, the material must have a higher thermal conductivity than the work piece in order to conduct heat away from the electrode-work piece interface. Choosing the appropriate electrode can reduce problems associated with electrode tip pickup and sticking, which in turn helps to reduce alloying between the electrode and work piece at the interface. Overall, there are many factors to be considered to fabricate the best electrode for a given application, but the proper electrode must have a certain minimum level of all three properties [13].

In order to achieve the appropriate balance of electrical and thermal conductivity and hardness, there are several variables of electrode choice that are significant to weld performance. Factors include material composition, overall size, cooling method, surface condition, and geometry. Changing any of these parameters changes the way the electrode and the work piece interact at the interface.

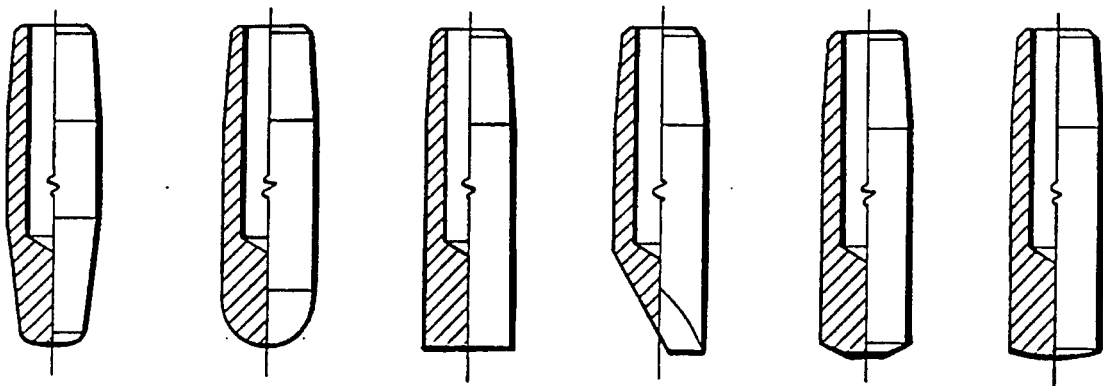
The material composition is important to defining the electrode's overall properties, but this research is primarily concerned with the interaction at the electrode-work piece interface for a number of reasons. Different material compositions have different electrical and thermal conductivity and different compressive strengths at weld temperatures. Additionally, and most importantly to this research, the electrode composition can prevent alloying of the electrode face with the work piece. Some

electrode compositions that are already being used to weld aluminum are zirconium copper, cadmium copper, and chromium copper [13].

The electrode size and the cooling method used impact the surface temperature and how much energy is dissipated within the electrodes. An electrode that is too small or cooled improperly will overheat and melt easier. One that is too large will be more electrically and thermally resistive and will require more energy to produce the same weld nugget size. Additionally, the electrode's compressive strength is a factor of overall electrode size [13].

The surface condition indicates the geometry at a microscopic level and is a factor in how the electrode breaks through the oxide on the surface of the aluminum. An electrode that is highly polished will have a different behavior than one that has a machined surface because of the manner in which it breaks through the oxide. An electrode that breaks through the oxide unevenly will be subject to a non-uniform current distribution, which can lead to further complications [7].

Finally, overall electrode geometry is dictated by how much surface deformation



**Figure 15 Electrode Geometry Variation (from Resistance Welding Manual, 4<sup>th</sup> Edition, George H Buchanan Co., Copyright 1995, p. 18-15)**

is allowable and how the electrode changes over time as it degrades. The cross-sectional surface area changes more rapidly for a domed electrode than it does with a truncated cone as the tip wears [7]. Another consideration for electrode geometry is the magnitude of the pressure applied, which will depend not only on the force, but also on the electrode surface area at the interface. Various electrode geometry configurations are shown in Figure 15 [13].

### 3.0 ELECTRODE PROCESSING TECHNIQUES

A variety of advanced processing techniques were utilized to modify the composition of copper electrodes. These are divided into two basic categories: surface treatments involving application of a refractory to the surface of the electrode and bulk techniques involving modification of the overall composition of the electrode.

#### 3.1 SURFACE TREATMENTS

##### 3.1.1 LASER CLADDING

Laser cladding is a process by which a coating can be applied to a surface. In this case, the coating, on the order of 400  $\mu\text{m}$ , was applied to the surface of electrodes. The process involves relatively simple theory. A focused laser beam traces

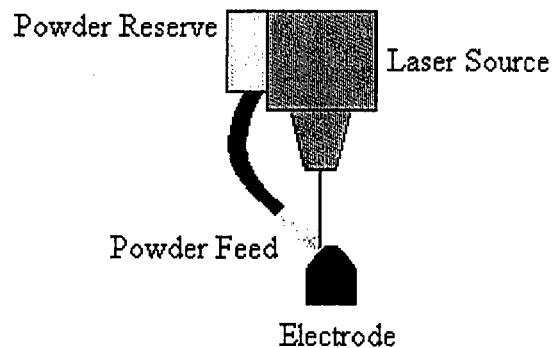


Figure 16. Laser Cladding Process

a path on the surface of the material to be coated while there is powder of the desired

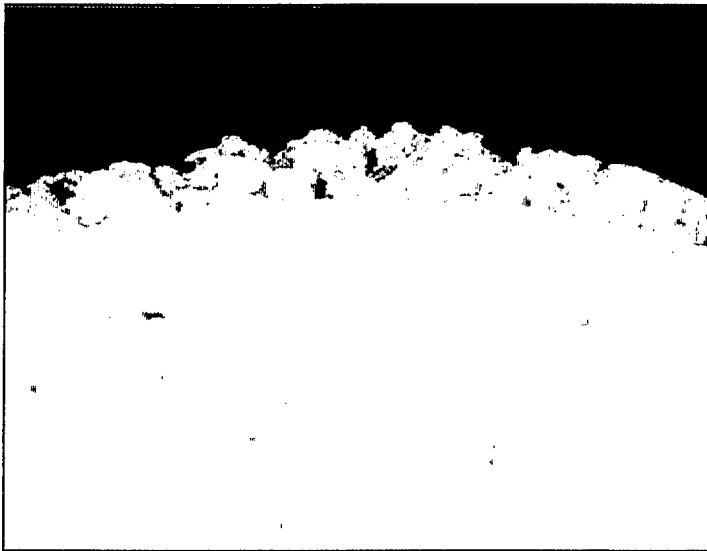
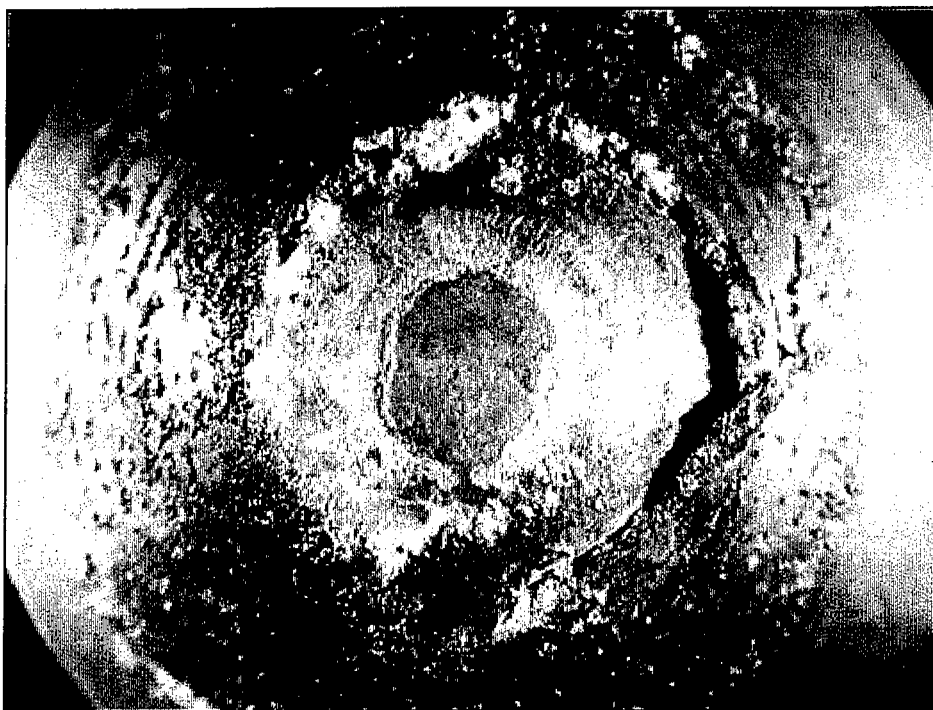


Figure 17. Laser Clad Surface, Before Welding

composition fed into the beam. Focussing the beam on the surface heats both the surface and the powder. The powder and a small layer of the surface melt, and a bond is formed between the powder and the surface. A diagram of the laser

cladding of a typical electrode is shown in Figure 16.

The University of Michigan's lab facilities in Ann Arbor, Michigan were used by University of Michigan Researchers to clad several electrodes to the specifications of this research, which were then subsequently tested at Ford. The laser clad electrodes were

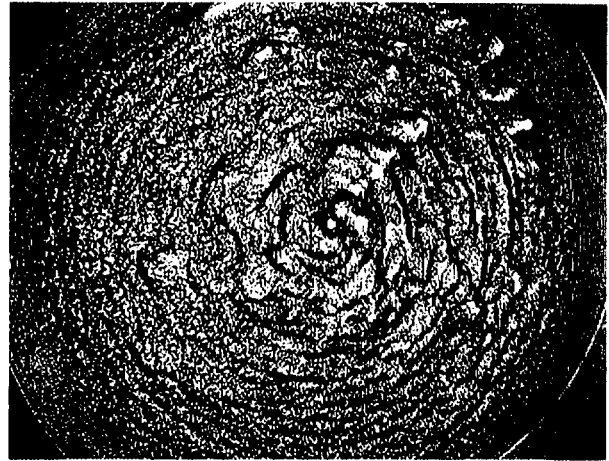


**Figure 18. Laser Clad Surface, After Welding**

tested in two batches. The preliminary testing was done to gather data to be used for parameter optimization and final test method development, and the final tests were done to compare the laser clad processing technique to other techniques tested.

The results for the preliminary batch of laser clad electrodes were tentative. Upon microscopic evaluation, it was clear that the laser clad coating was very porous and that the molybdenum was unevenly distributed after processing but before welding. If the molybdenum is not distributed uniformly, the properties of the electrode will not be

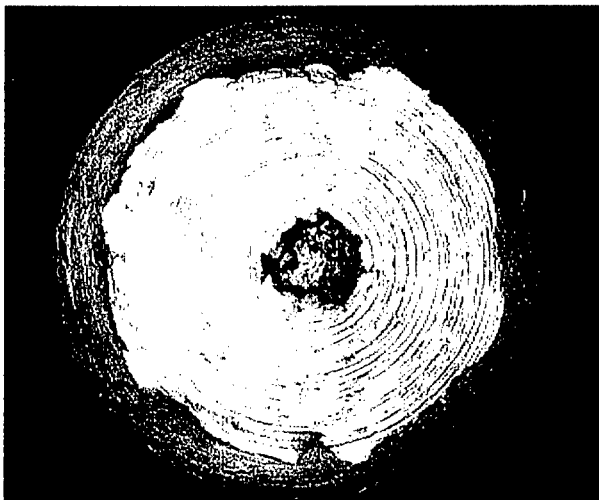
significantly different from the base metal without the alloy or added element. The coating of one of the preliminary electrodes produced for this study taken before welding can be seen magnified 25 times in Figure 17. The



**Figure 19. Non-Machined Laser Clad Coating**

coating was left rough in order to determine the amount of machining

necessary and, as a result, there was severe sticking between the electrode and the work piece that caused the coating to be removed during welding. Looking at the separation under an optical microscope, it appears that the copper-molybdenum powder did not bond with the surface of the electrode completely. This is apparent by the machining lines that are still visible on the surface of the electrode underneath the area where the coating was applied. A photograph of the electrode taken after welding can be found in



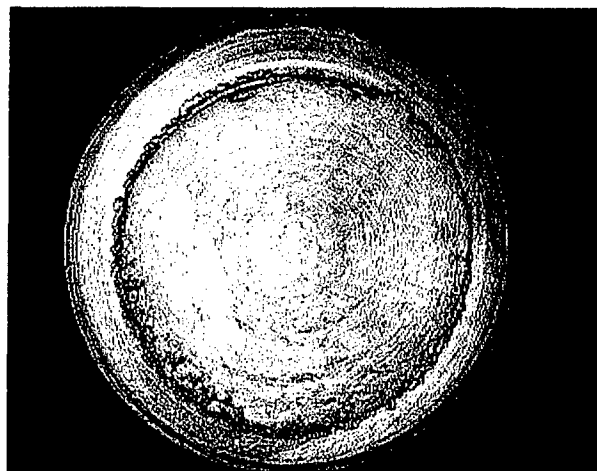
**Figure 20. Machined, Porous Laser Clad Coating**

Figure 18. The result of the lost coating was a relatively large weight and length loss from these electrodes as compared with the non-coated electrodes.

During the final evaluation, more tests were performed on laser clad electrodes. For the laser clad samples, there are parameters that can be changed



within the processing possibly to achieve better results. The surface of the electrode can be roughened using hard pellets or it can be painted with a thin graphite layer. Both of these solutions would target the reflectiveness of the copper. It is a very good reflector naturally and, as a result, much of the



**Figure 21. Machined Laser Clad Coating**

laser's energy is reflected off the surface. Additionally, other changes can be applied, including adjusting the rate of powder feed, the gap between passes, laser power, and advance speed. Changing these parameters could lead to a better bond between the copper electrode surface and the copper-molybdenum powder that is sprayed into the beam of the laser. The parameters were held constant for this study in order to increase consistency, but could be considered in future research.

After collecting the results from the preliminary testing, a change was made that improved the electrode performance slightly. By polishing or machining the surface of the laser clad electrodes prior to welding, a smoother surface was created that provided a more consistent surface topography. Since a smooth surface geometry of the electrode is important for proper oxide break-up as well as electrode and work piece interaction, the smoother surface behaved better than the rough surface. The machining that was done was a simple process done at the Ford Research Laboratory on a lathe. Machining the laser clad coating revealed some macroscopic pores in many of the electrodes. Similar pores beneath the surface can result in an uneven current distribution and subsequently a

bad weld. Figures 19, 20, and 21 show a comparison between an electrode without machining, one machined and porous, and one machined with a good coating, respectively. Porosity in the coating is minimized by proper processing techniques.

The scanning electron microscope was used to reveal the break in the bond between the laser clad coating and the surface of the electrodes. In addition, microscopic analysis revealed microscopic pores and molybdenum precipitates within the clad coating. Because of the microscopic pores and the uneven distribution of molybdenum, the properties of the clad portion were not consistent across the face of the electrode.

### 3.1.2 PLASMA SPRAYING

Plasma spraying is a process, as seen in Figure 22, by which there is a thin coating, measuring approximately 40  $\mu\text{m}$  in thickness, applied to the surface of a substrate.

In the case of this research, the substrate is a copper electrode and the coating is the refractory metal

niobium. The niobium was melted and the molten plasma was then sprayed through a nozzle onto the surface of the electrode. A fabrication company called Plasma Processes located in Huntsville, Alabama provided a sample of electrodes for use for this research of which three were chosen based on macroscopic appearance.

It should be noted that, due to availability of materials, the plasma sprayed electrodes have a different geometry than the other processed electrodes. While this factor is important for electrode performance maximization, useful data pertaining to plasma sprayed coating were still able to be obtained.

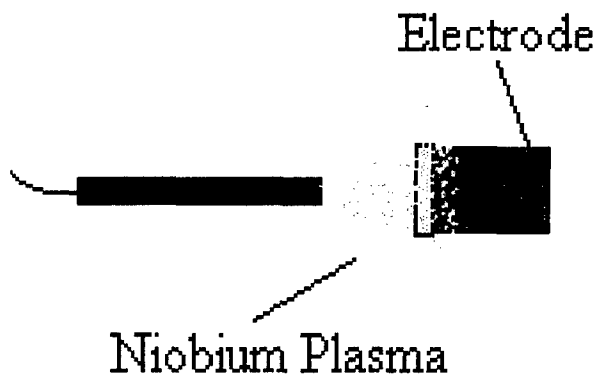
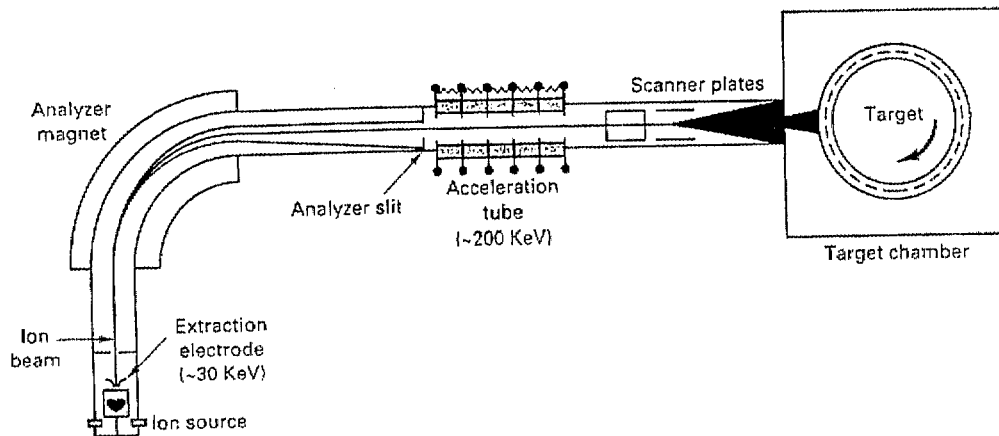


Figure 22. Plasma Spraying Process

### 3.1.3 ION IMPLANTING

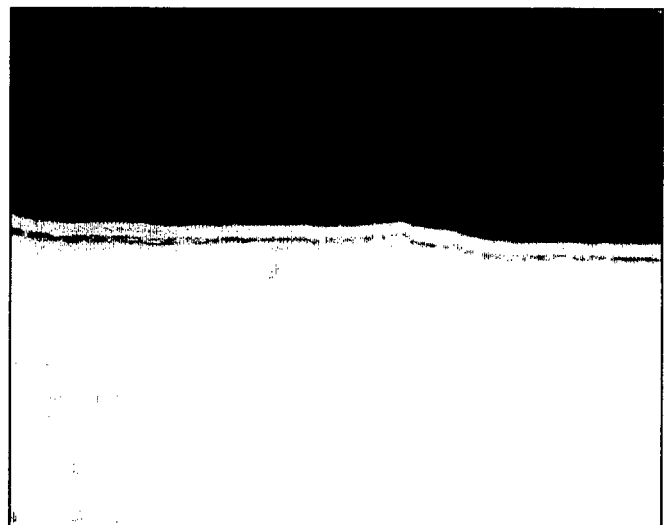
Ion implantation is a process by which ions of the desired alloying element are imbedded in the surface of the substrate. Shown in Figure 23, the ions are given a high



**Figure 23. Ion Implantation (from Materials and Processes in Manufacturing, Eighth Edition, Prentice Hall, Copyright 1997, p. 1109)**

level of kinetic energy while they pass through an evacuated particle accelerator. Upon reaching the substrate, the kinetic energy is lost through multiple collisions and the ion comes to rest beneath the surface of the substrate [2].

Electrodes were processed initially using ion implantation, but it was found by researchers at the Naval Research Laboratory in Washington, D.C. using X-ray Photoelectron Spectroscopy that the penetration of the ions was approximately 300 Angstroms. This distance converts to



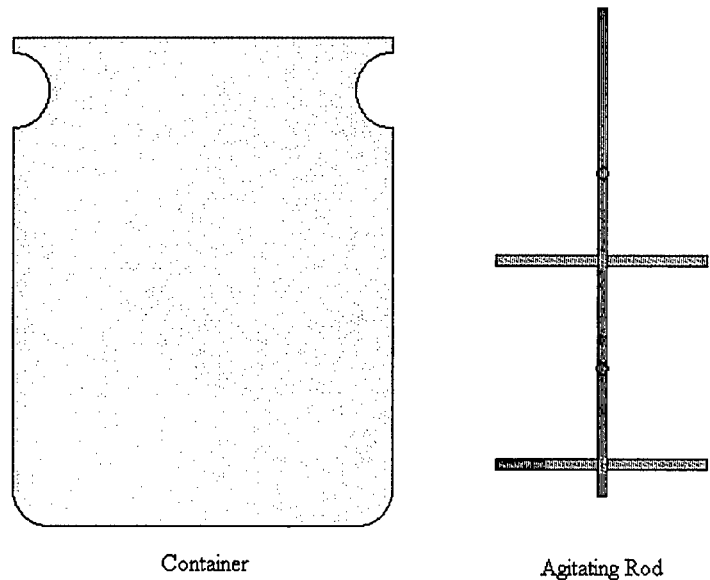
**Figure 24. SEM Photo of Ion Implanted Surface (1000x)**

$3 \times 10^{-4}$  mm below the surface. The depth of penetration magnified 1000 times can be seen in Figure 24 in a picture taken at USNA. Since typical stock electrode length loss measurements were almost 1000 times that distance, it was determined that the ion implanting would not provide an effective barrier against eutectic formation and further tests were not performed.

## 3.2 BULK TREATMENTS

### 3.2.1 MECHANICAL ALLOYING

Mechanical alloying is a powder metallurgy processing method that was used to produce higher molybdenum content in the copper electrode. This work was performed with the cooperation of the Naval Research Laboratory (NRL). In this process, metal powders (copper and molybdenum in this



**Figure 25. Impeller Rod and Stainless Steel Drum**

case), less than 40  $\mu\text{m}$  in size, were combined mechanically in a stainless steel drum. Along with the powders, small stainless steel balls and mineral spirits were added. The mixture was agitated using a rod fitted with a number of impellers that fit inside the container. As the rod rotated, the impellers transferred kinetic energy to the balls, which in turn used that energy to weld the powders together. This process continued at a specified rotational speed for a predetermined amount of time. This resulted in the powders first being broken down into smaller sizes and then being crushed together repeatedly. The theory holds that the powders will bond with each other on a microscopic scale, thus achieving a uniform distribution of the molybdenum within the copper [15]. A diagram showing the mechanical alloying container and agitating rod can be found in Figure 25.

After the powders were fully mechanically alloyed, they were compacted by Cold Isostatic Pressing (CIP) at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. In this process, the powders were placed in a cylindrical can and pressure was applied uniformly while the powders and can were being held at a slightly elevated temperature. The desired final product was a rod made from copper with eight percent molybdenum by weight evenly distributed. Following processing, three electrodes of the same size and shape as the stock electrodes were machined from the produced rod.

### 3.2.2 POWDER BLENDING

This process is a simpler form of powder metallurgy than mechanical alloying. Instead of using a high-energy



Copper Can

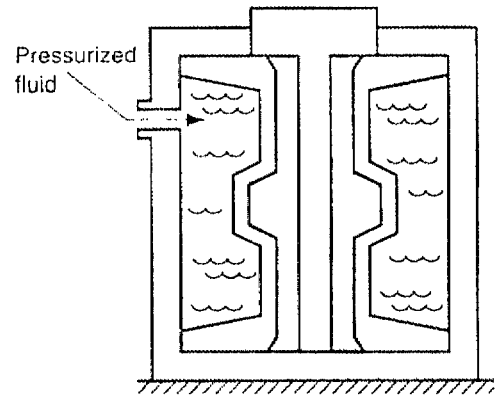


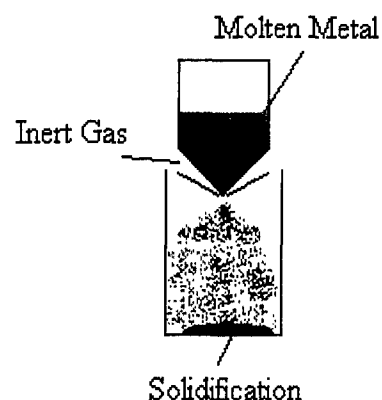
Figure 26. Copper Can and Pressure Vessel

ball mill to grind the powders and weld them together on a microscopic scale, this process consisted of simply mixing, or blending, the powders together. The blended powders were then processed in a manner very similar to the mechanically alloyed powders in which a compaction can is inserted into a pressure vessel. Fluid pressure and increased heating are then applied simultaneously. The powders, made up of copper with eight percent chromium and four percent niobium, were blended and then Cold Isostatically Pressed in a copper can at the National Institute of Standards and Technology (NIST) at 800 degrees Celsius for a period of four hours to form a rod of the desired composition from which three electrodes were machined. A schematic showing a copper compaction can that is placed inside a pressure vessel similar to the one used to CIP the powders is shown in Figure 26.



### 3.2.3 SPRAY FORMING

Spray forming is a processing technique by which a material with a given composition is made by the rapid solidification of tiny molten droplets of the desired composition. The desired components in the proper composition of the final product are combined in a molten state inside a crucible. The molten metals are then atomized in a collection chamber by a high velocity stream of inert gas. The inert gas serves the



**Figure 27. Spray Formation Process**

additional purpose of cooling the molten droplets and helping them solidify as they are collected on a substrate inside the spray chamber. This process can be seen in Figure 27. In this case, the material was primarily copper with chromium intermixed. The mixing and spray depositing were accomplished for this research at the Carderock Division of the Naval Surface Warfare Center and the bulk product was machined into three electrodes.

The advantages of spray forming are that it can be used to produce material in a form close to its desired shape and improved material properties. This results in less required machining and properties similar to those obtained from powder metallurgy processing without ever handling the metals in powder form.

## 4.0 ELECTRODE EVALUATION

Determining the potential for an electrode processing technique to be used for mass production requires evaluation of not only the electrode wear, but also quality of the weld produced. This section discusses the methods used to quantify both electrode degradation and weld quality over time.

### 4.1 EVALUATION METHODS

The material loss test as quantified by mass and length loss is an indicator of comparative performance of one electrode to another, but it is not necessarily a predictable measure of electrode lifetime. This is due to the fact that the surface condition and geometry is much more important than overall material loss [7]. It does, however, give an indication of whether or not there has been an improvement in a

particular electrode. It is an advantageous method for testing new electrodes because it does not require as many test samples.

Given the cost and difficulty of processing a small quantity of

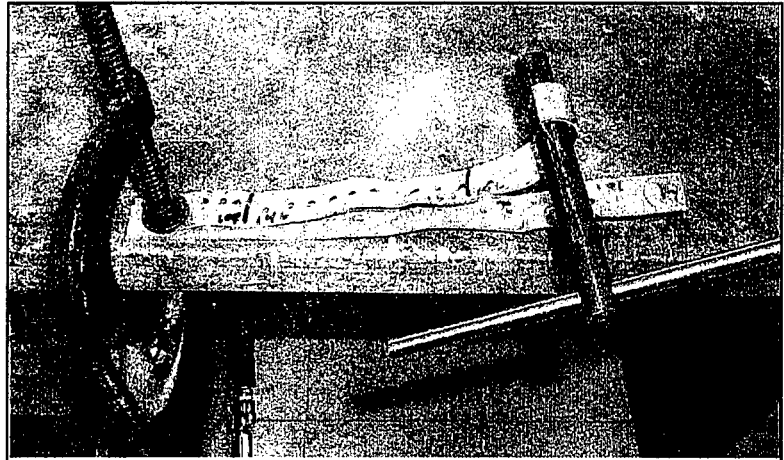


Figure 28. Peel Testing

electrodes, it is practical to assess a limited number of specimens using a material loss test to indicate promising processing methods. After a processing method has been

identified as having lifetime extending potential, time and resources can be devoted to proceeding with a lifetime test of many samples.

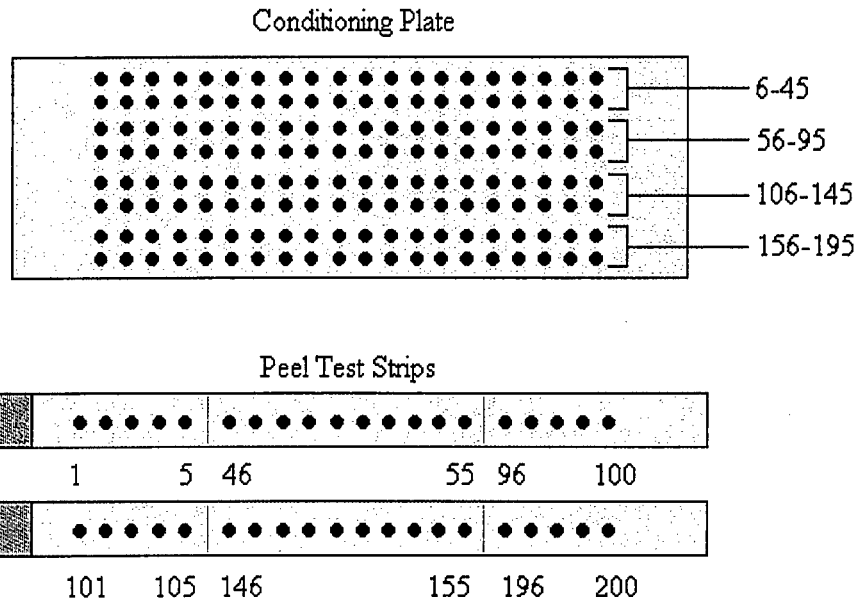
Another experiment that is done to measure electrode lifetime is a conditioning and peel test schedule. First, a given number of welds are made on a conditioning plate in what is termed the conditioning phase. Following the predetermined number of welds, a relatively smaller number is made on a test strip. The test strip is then peeled apart, as seen in Figure 28, and the minimum diameters of the weld nuggets are measured. A particular weld is considered a bad weld if the minimum diameter does not meet a certain requirement. If the number of bad welds on the test plate exceeds a given criterion (for example, more than two bad welds in a sample of five), the lifetime of the electrode is considered to be the number of welds that were made prior to the last test plate. If enough of the welds on the test plate are good welds, the cycle is continued with another conditioning phase followed by a test plate. The test continues until failure of the electrode is reached [7].

## 4.2 COMPOSITE TEST METHOD

The two test methods described above were combined to design a test for a limited number of samples in a batch composed of electrodes made from several different

Weld #	Location	
1-5	Peel Strip	The composite test consisted of a mass and length measurement before and after welding as well as a number of peel test specimens. In order to achieve as much consistency as possible between the different electrodes, the test schedule was the same for each electrode. Each consisted of 200 total spots, broken down as shown in Figure
6-45	Conditioning Plate	
46-55	Peel Strip	
56-95	Conditioning Plate	
96-105	Peel Strip	
106-145	Conditioning Plate	
146-155	Peel Strip	
156-195	Conditioning Plate	
196-200	Peel Strip	

**Figure 29. Weld Test Schedule**



**Figure 30. Conditioning Plate and Peel Strips**

29. This breakdown was designed to give a representative weld nugget at many stages of

degradation, including initial and final weld nugget size for comparison. The test plate weld configuration can be seen in Figure 30.

At Ford's Scientific Research Laboratory in Dearborn, Michigan, a series of welds was made for this research project using various electrodes. The objective was to measure the mass and length loss over a given number of welds. As will be seen in the Results section on page 59, graphs were produced showing a possible correlation between material loss and processing technique.

The results of the composite testing are separated into three categories: observations made while welding, mass and length loss over time, and peel test indication of weld quality. Specific electrodes did not necessarily stand out in each category, but some findings give a strong indication of the viability of using a particular electrode for mass production.

### 4.3 STRUCTURAL ANALYSIS TECHNIQUES

By using microscopy to analyze the electrodes before and after welding, it is possible to develop hypotheses explaining trends observed from the quantitative data. Both optical and scanning electron microscopy consist of using high magnification to observe unique features and characteristics and identify phase formation. These techniques and the USNA instruments utilized are detailed below.

#### 4.3.1 OPTICAL MICROSCOPY

Analysis of a sample using the magnification of light through a series of lenses is called optical microscopy. It is usually limited in magnification, up to approximately 1000 times. It does give a color image of the sample, however, which is often beneficial

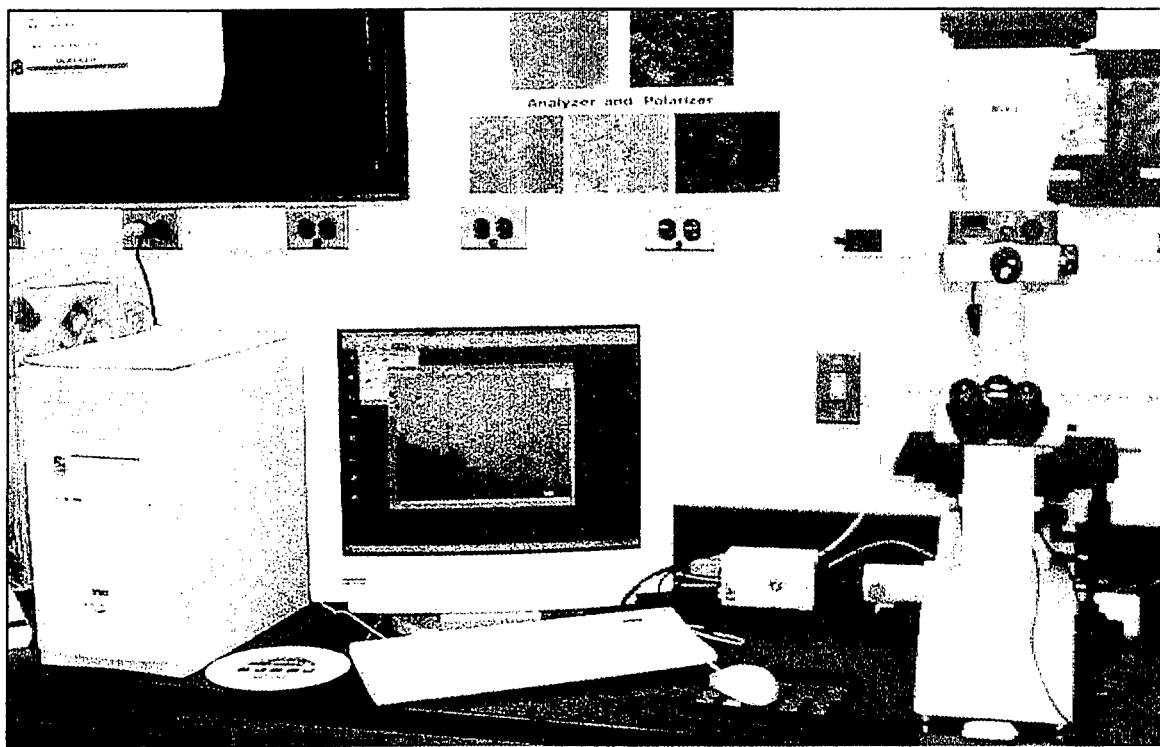
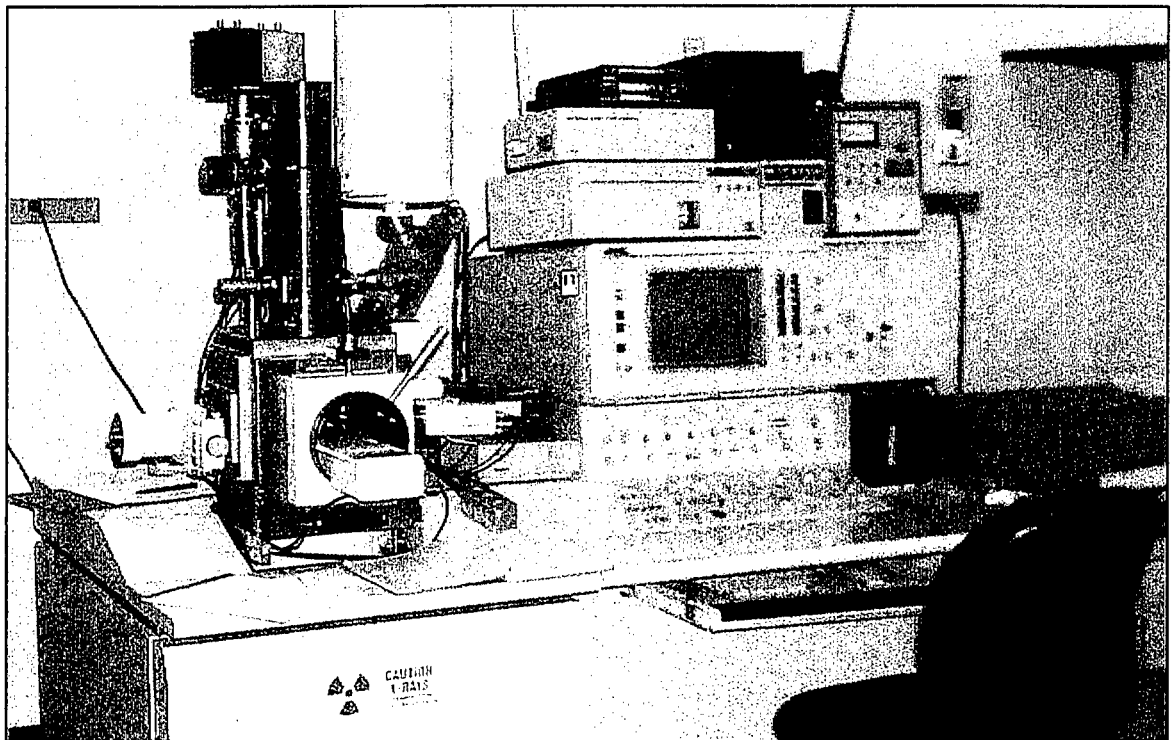


Figure 31. Optical Microscope

during analysis. For this effort, the electrodes had to be prepared using several steps before they could be viewed using the optical microscope, a Nikon Epiphot with Clemex Image Analysis capabilities, seen here in Figure 31. Sample preparation included cutting a cross-section of the electrode that passes through the area of interest, mounting the sample in a silicone based disc, and polishing thoroughly to remove any evidence of damage from sectioning or mounting. This polishing method is the same as used for preparing samples for the Scanning Electron Microscope (SEM).

### 4.3.2 SCANNING ELECTRON MICROSCOPY

After preparation as discussed in section 4.1, the samples were also ready for viewing in the Scanning Electron Microscope (SEM). The SEM, a JEOL 6100 with KEVEX Quantitative Image Analysis, seen in Figure 32, operates by directing a thin beam of electrons at the surface of the sample and then detecting the emissions that

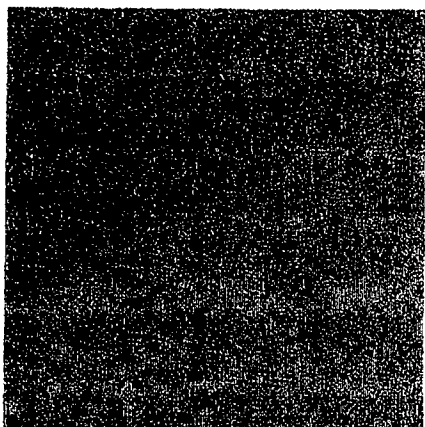


**Figure 32. Scanning Electron Microscope**

result. The beam traces a path back and forth, or scans, across the surface and assembles the information to produce a complete picture of the sample. Using this technology, the sample can be magnified hundreds of thousands of times.

Another analysis tool available with the SEM is called X-ray mapping. This process takes advantage of the fact that each element emits energy of a characteristic wavelength when excited. By detecting which specific wavelengths come from which specific areas on the sample, it is possible to create an image showing where on the





**Figure 33. Aluminum X-ray  
Map**

section of an electrode or a weld nugget.

sample certain elements are concentrated. An example of an X-ray map is shown in Figure 33. The map is very simple to analyze: the darker the color on the image, the more concentrated the element in the sample. In Figure 33, for example, the intensity of the red color is proportional to the concentration of aluminum in that region. This makes it possible to tell what elements are present and where in the cross-

## **5.0 ELECTRODE PROCESSING RESULTS**

In this section, electrode test results are presented. Data on each electrode spans the entire test of 200 welds and includes mass and length loss measured, average nugget size, and good weld rate, which is presented as the percentage of tested welds that met the minimum diameter requirement.

## 5.1 SURFACE TREATED ELECTRODES

### 5.1.1 LASER CLADDING

The final laser clad batch after machining did not produce more promising results than initial tests described in section 3.1.1, which were performed to optimize the processing technique. A micrograph of the electrode's surface before welding can be found in Figure 34. The clad surface was highly porous and molybdenum precipitates can be seen at fairly low magnification. During welding, there was significant sticking of the electrodes to the surface, cracking, delaminating, and deformation of the coating. The severely damaged electrode after welding is seen in Figure 35.

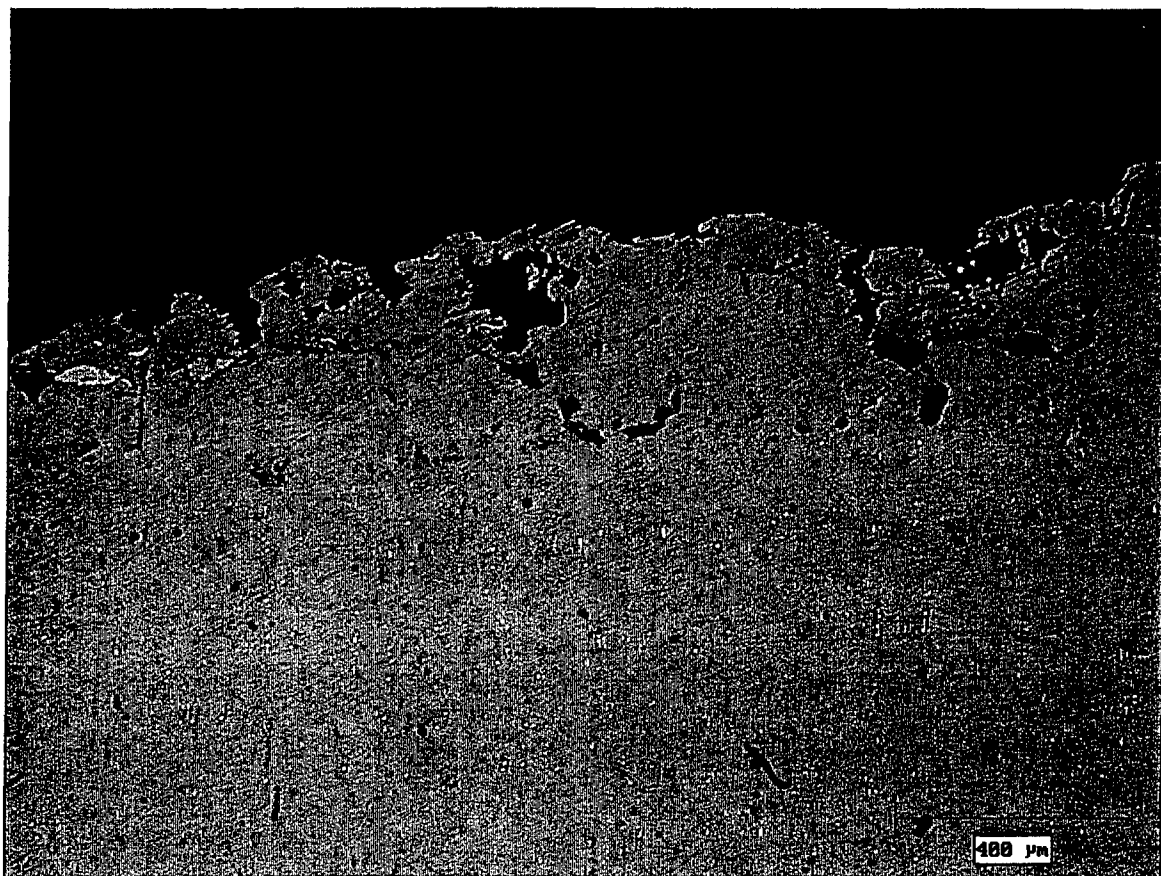
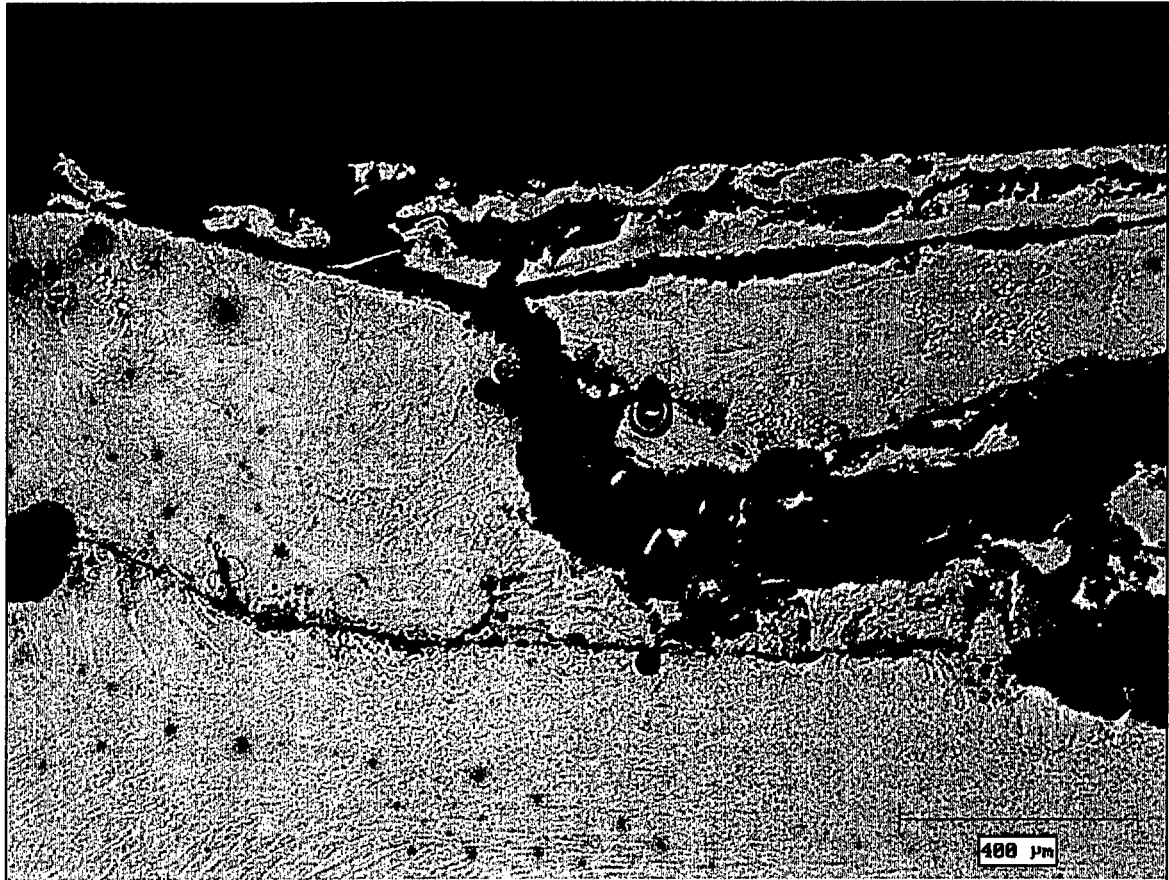


Figure 34. Laser Clad Surface, Before Welding (50x)

The measured mass loss was 105.2 mg and 0.748 mm total length was lost. This was among the highest measures of material loss among all the electrodes. The weld quality was much better than the other surface treated type tested, which was plasma sprayed, but fell well short of the bulk processed electrodes with an average nugget size

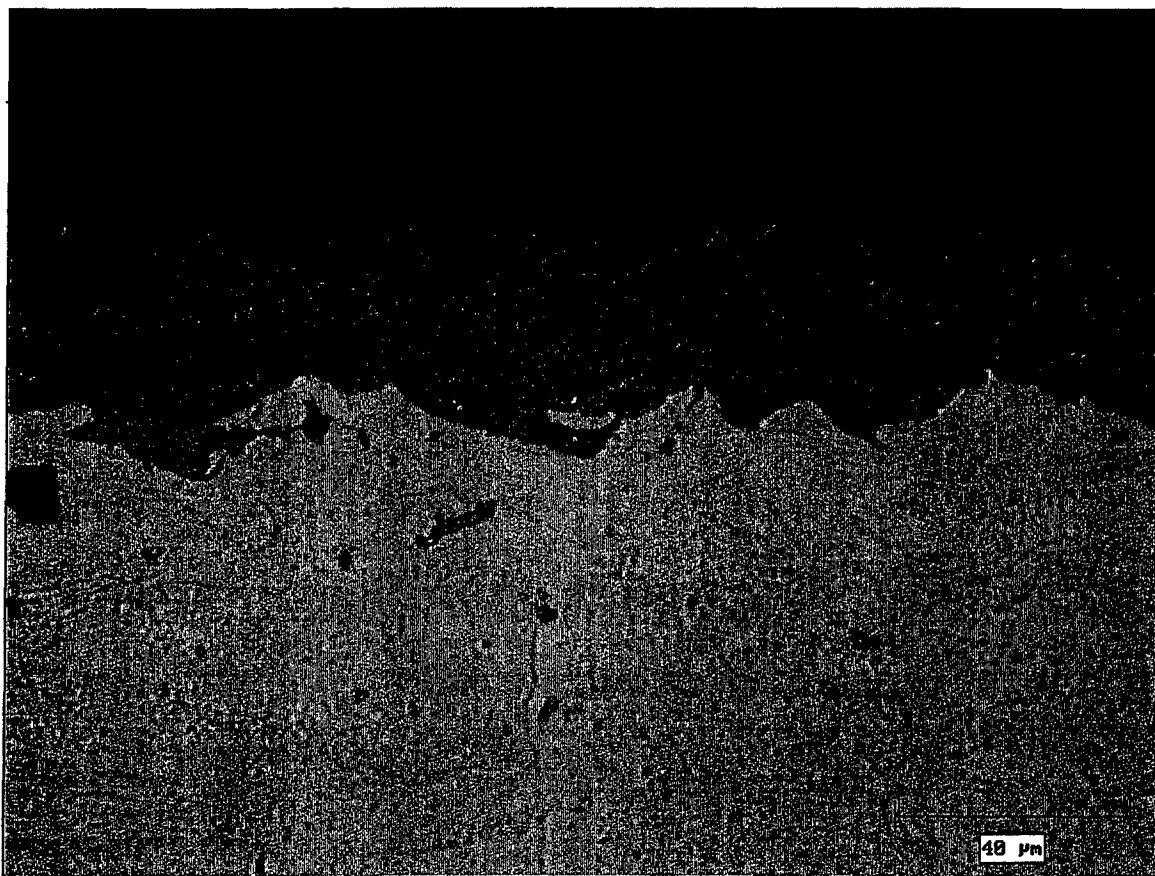


**Figure 35. Laser Clad Surface, After Welding (50x)**

of 4.267 mm and a 65 percent good weld rate. The results are presented in Table 4, on page 62, at the end of the section.

### 5.1.2 PLASMA SPRAYING

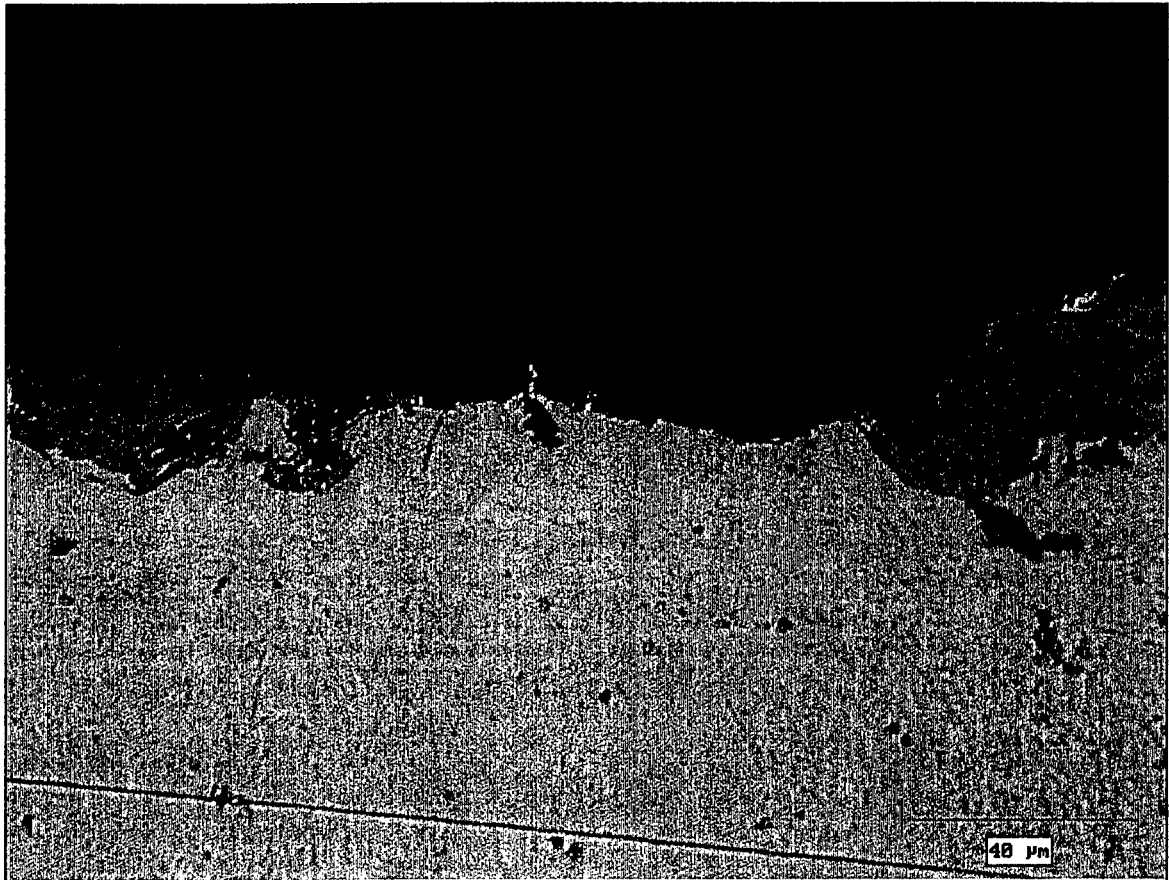
After processing, the surface of the plasma coated electrode resembled that of a fine-grade sandpaper. The thickness of the niobium coating was measured using optical microscopy to be approximately 40  $\mu\text{m}$ . The thickness of the coating was relatively uniform, although variation of up to 10  $\mu\text{m}$  was noted. An optical micrograph of the plasma sprayed electrode magnified 500 times can be found in Figure 36.



**Figure 36. Plasma Sprayed Electrode, Before Welding (500x)**

During testing, the niobium coating burned off as a result of the first weld. Evidence of this phenomenon is found in a picture of the plasma sprayed electrode after welding, magnified 500 times, as in Figure 37. The cause of the melting was most likely

a result of lower conductivity in the niobium and elevated contact resistance at the electrode-work piece interface. The welds following the failure of the coating exhibited a higher occurrence of bad welds than traditional electrodes. Overall, the plasma sprayed electrode produced the most limited results. The material loss measurements reflected



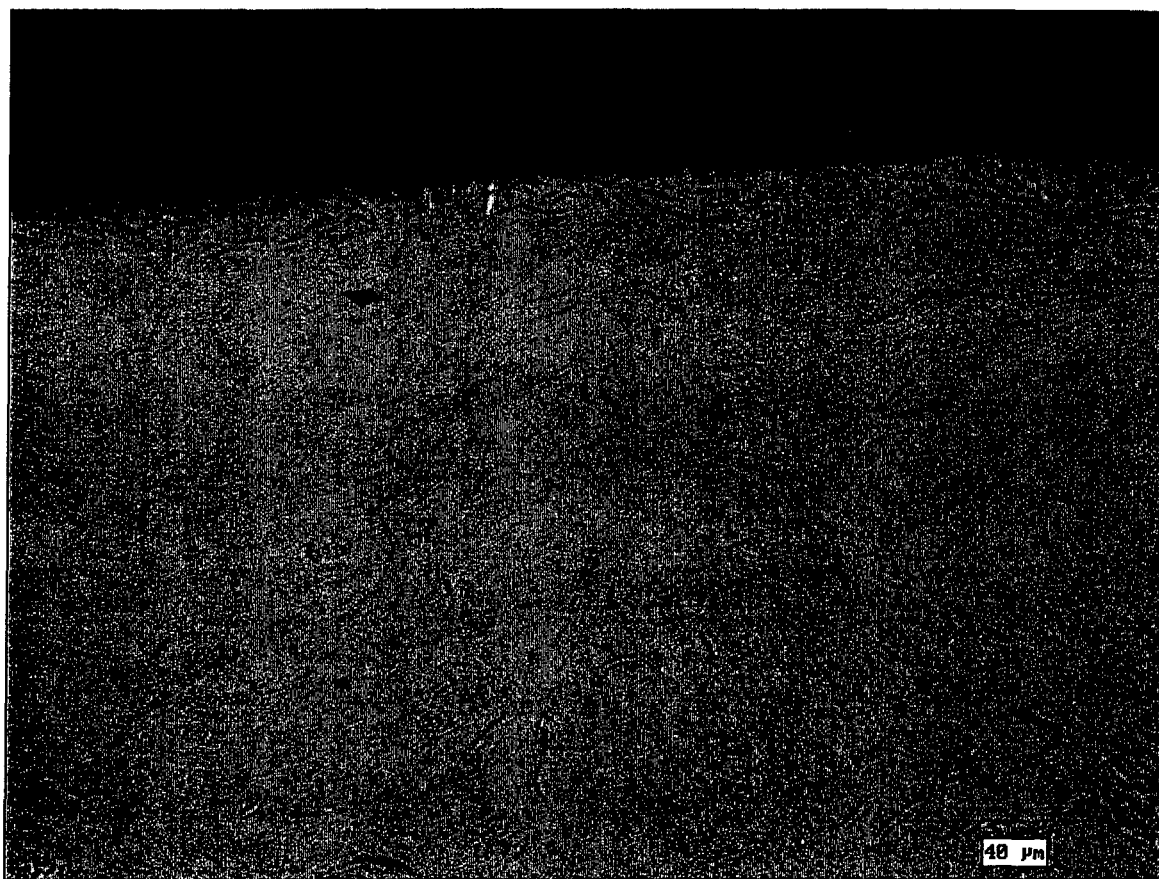
**Figure 37. Plasma Sprayed Electrode, After Welding (500x)**

the lost coating at 25.6 mg and 4.702 mm. The average nugget size was a very small 0.686 mm and the good weld rate was just 12.5 percent. These data are presented in Table 4.

## 5.2 BULK TREATMENTS

### 5.2.1 MECHANICAL ALLOYING

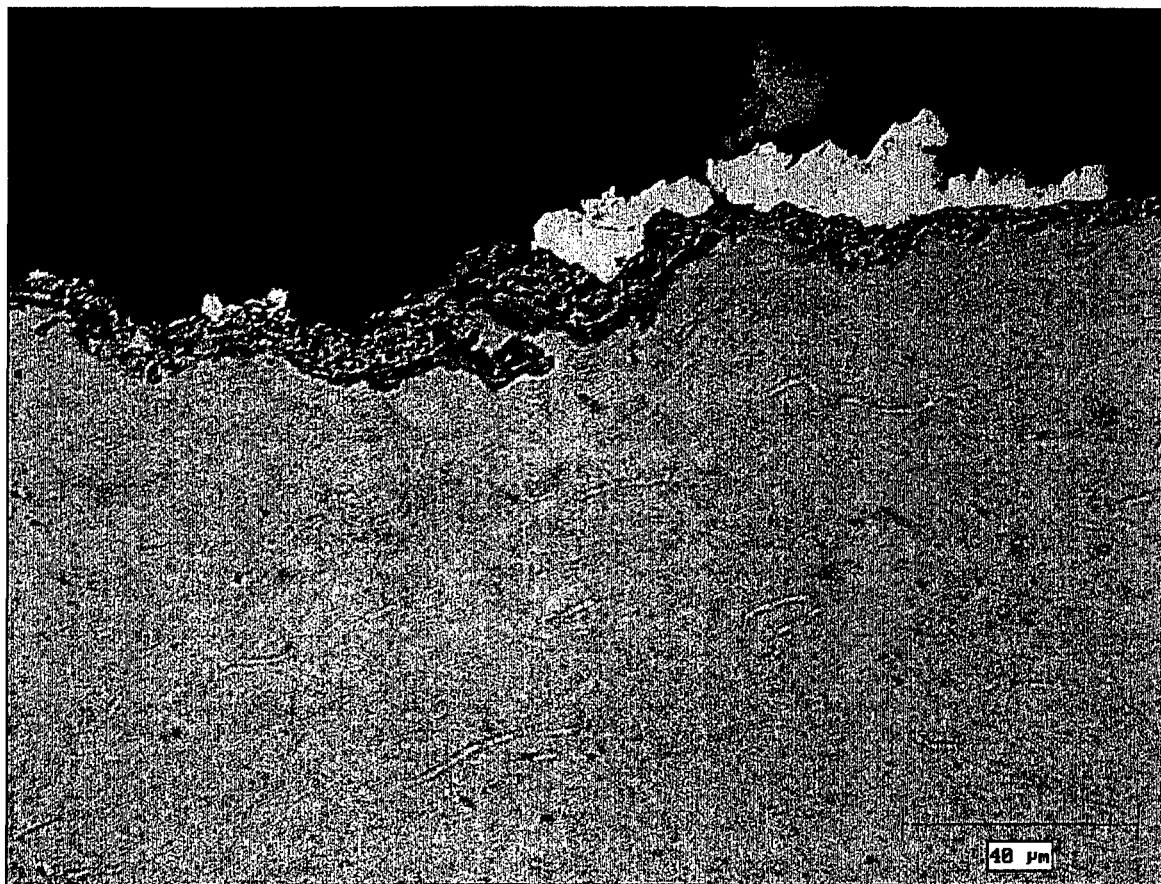
The mechanically alloyed sample showed considerable precipitation of the molybdenum throughout the copper, as seen in Figure 38. The molybdenum was found



**Figure 38. Mechanically Alloyed Electrode, Before Welding (500x)**

in strips approximately 1 - 2  $\mu\text{m}$  wide and 10 - 40  $\mu\text{m}$  long. After welding, as seen in Figure 39, the molybdenum within the body of the electrode remained relatively unchanged in size or shape. At the surface, however, the molybdenum was found concentrated along the surface of the electrode. In this position, the molybdenum acted as a shield between the aluminum work piece and copper electrode. This resulted in

better weld quality throughout the 200-weld test. The material loss is still significant, however.



**Figure 39. Mechanically Alloyed Electrode, After Welding (500x)**

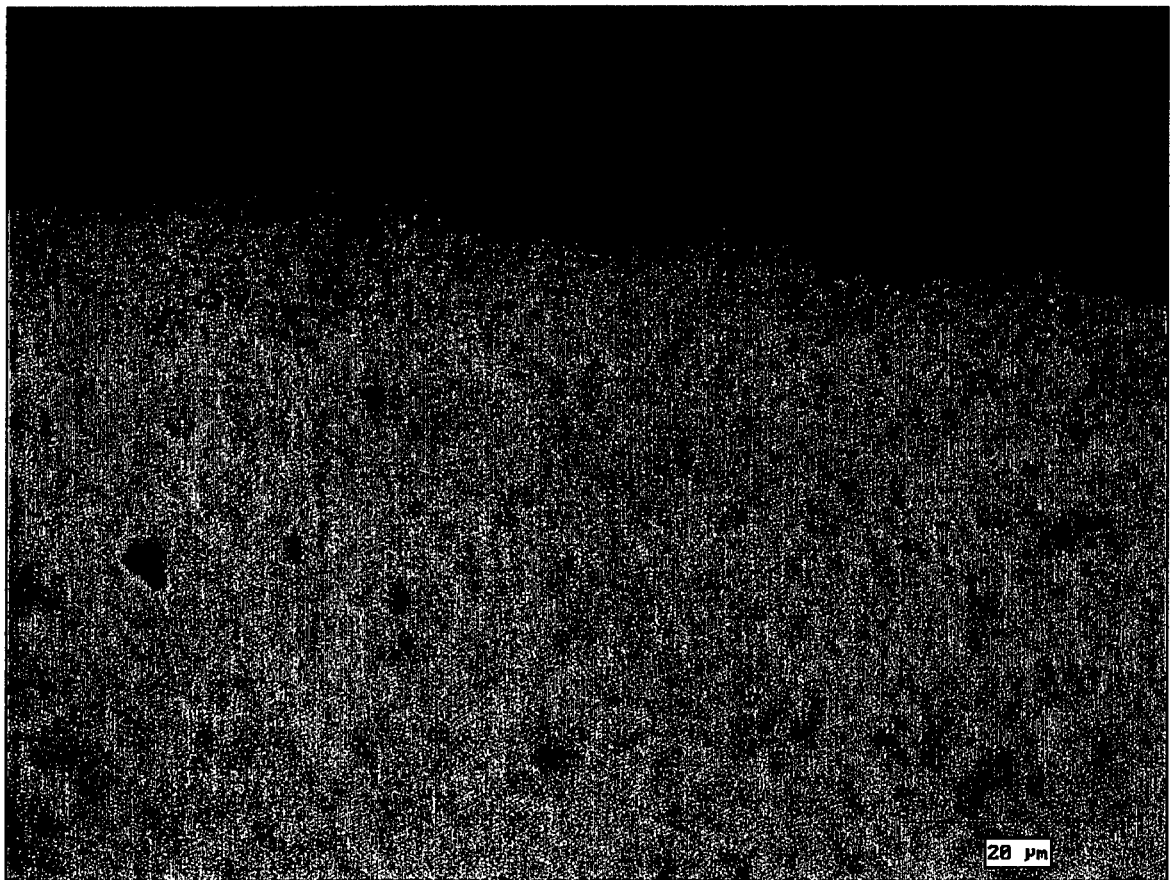
It is hypothesized that the copper melted and was degraded away initially via the eutectic formation. Then, since molybdenum is not susceptible to the eutectic degradation, a layer of molybdenum built up on the surface and the copper was protected from aluminum diffusion and degraded less rapidly. The molybdenum build-up on the surface is similar to a snowball intermixed with sand. On a hot day as the snow melts on



the top surface of the snowball, the sand layer becomes thicker. This process would continue until the sand layer is thick enough to act as insulation from the sun and slow the melting of the snowball. Supporting the sandy snowball hypothesis, the electrode did lose a significant amount of material initially. In addition, weld quality was good early in the weld schedule and then nugget size decreased near the middle. With further welding, however, the nugget size increased. The total mass loss measured was 31.02 mg and 0.068 mm was lost in overall length. The weld quality results were much better than the surface treated techniques at an average nugget size of 4.394 mm and a good weld percentage of 80.0. A table comparing the results of all the electrodes is found in Table 4.

### 5.2.2 POWDER BLENDING

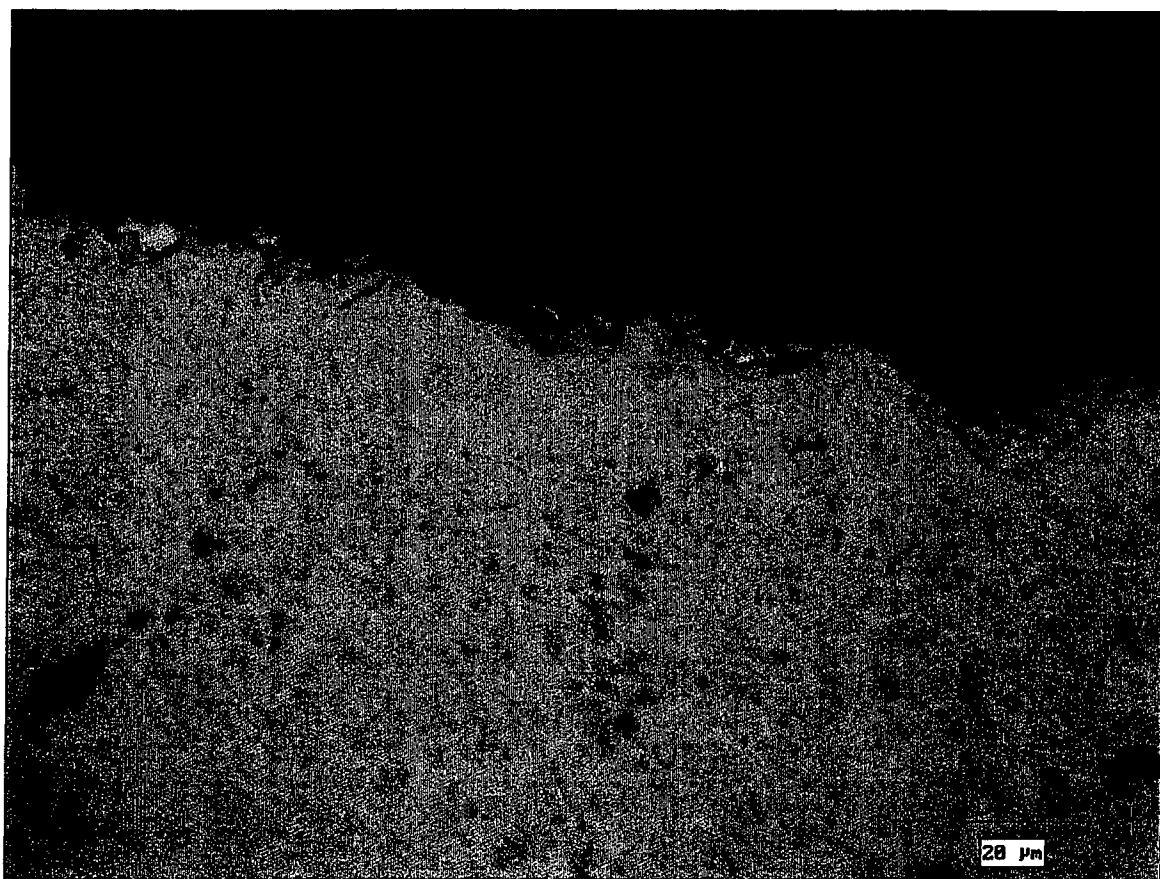
Optical microscopy of the powder blended electrodes revealed a behavior very similar to the mechanically alloyed samples. Initially, the electrode is copper with even distributions of refractory throughout, as seen magnified 1000 times in Figure 40. The refractory precipitates in this case were more spherical and approximately 2 to 10  $\mu\text{m}$  in



**Figure 40. Powder Blended Electrode, Before Welding (1000x)**

diameter. After welding, however, evidence of the same refractory protection layer production was found. In the picture of the electrode after welding, in Figure 41, a dark gray layer of chromium and niobium can be seen on the electrode.

Additional analysis was done through the use of X-ray mapping. Four maps, showing copper, chromium, niobium, and aluminum are shown in Figure 42. The maps reveal a concentrated layer of chromium and niobium refractory metals on the surface as hypothesized. It is also worth noting that the aluminum from the work piece is entirely on the surface, not significantly mixed with the copper.



**Figure 41. Powder Blended Electrode, After Welding (1000x)**

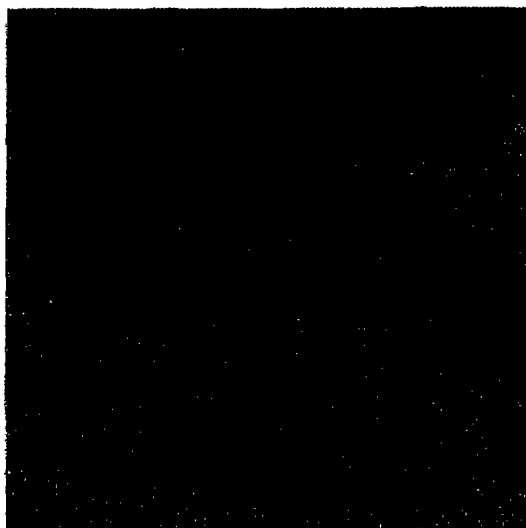
Although there was a significant amount of material lost initially, 2,259.0 mg, the length loss was comparable to the others at 0.167 mm. The weld quality tests, however, were better than any other electrode with a nugget size of 4.547 mm and a good weld rate of 92.5 percent. Presented in Table 4, it is easy to see that the powder blended electrode stands out among the rest.



**Copper**



**Chromium**



**Niobium**

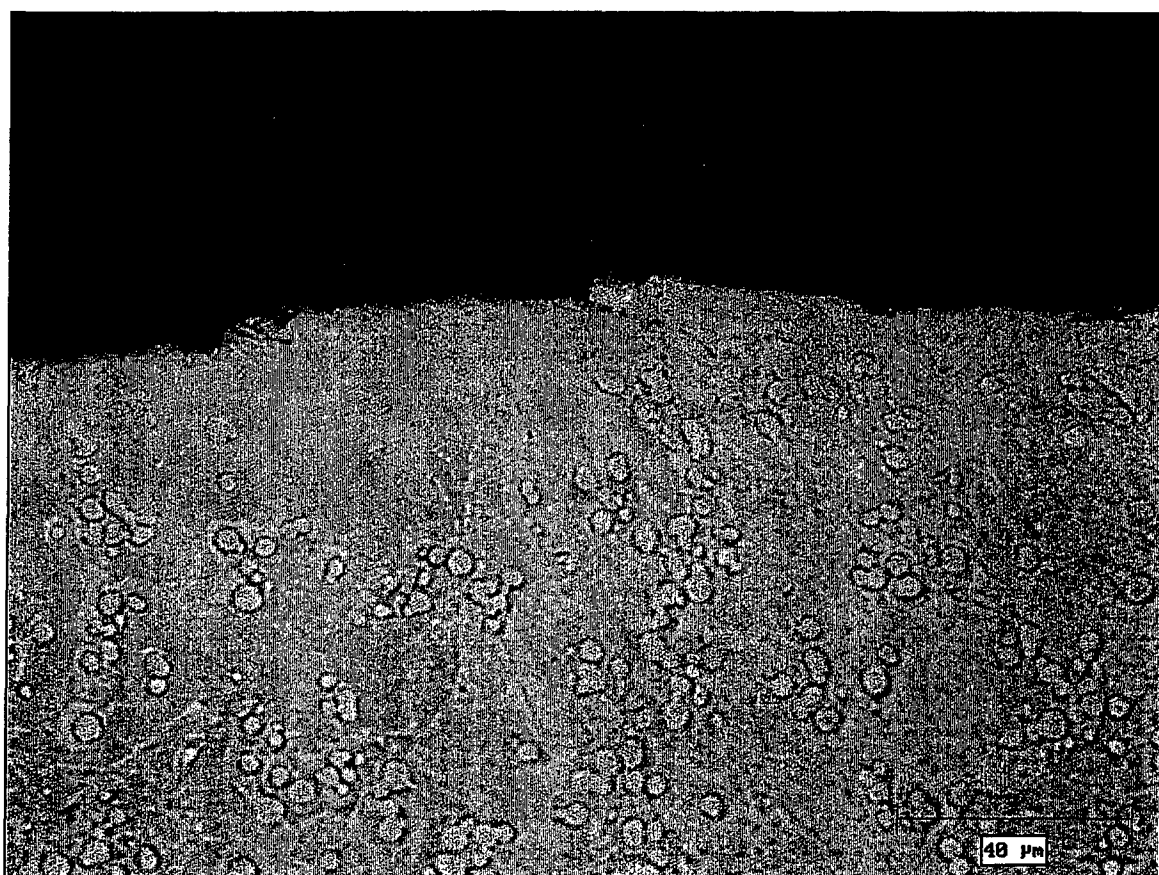


**Aluminum**

**Figure 42. X-ray Map of Powder Blended Electrode After Welding**

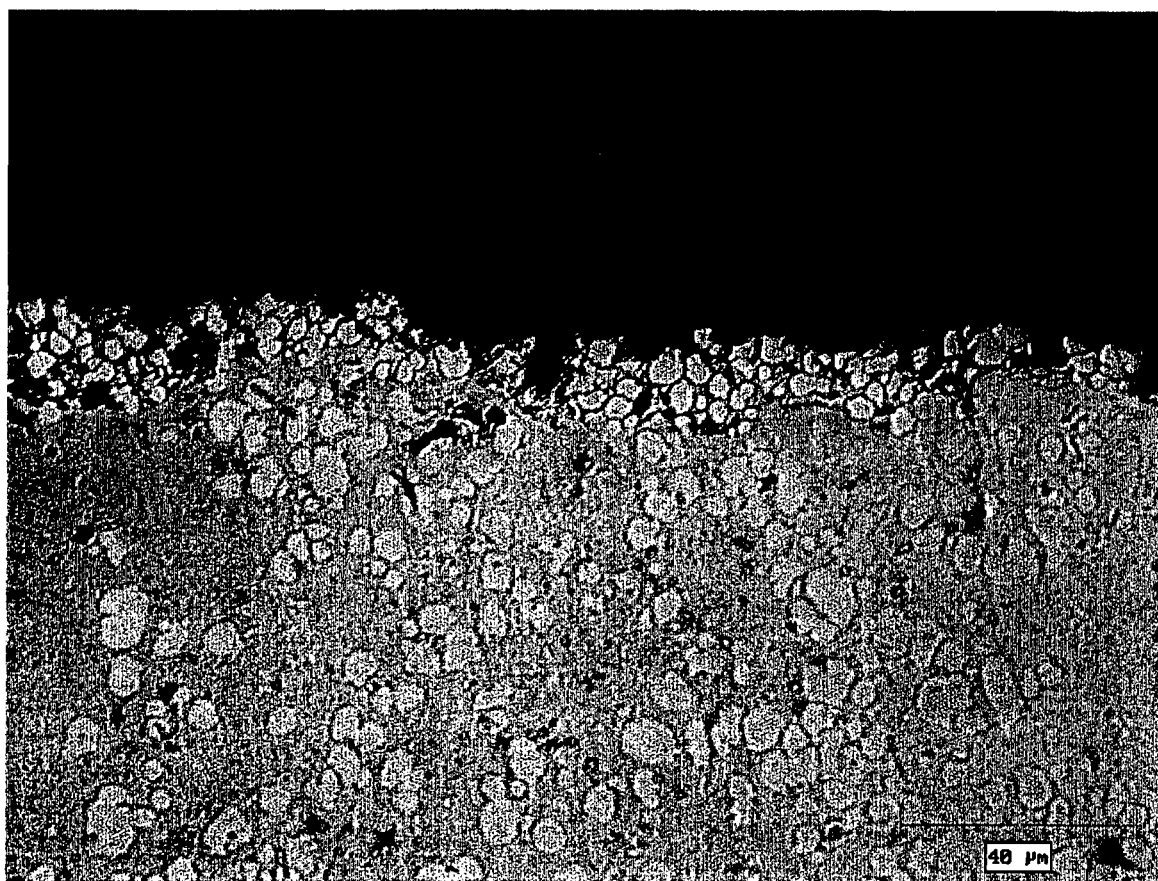
### 5.2.3 SPRAY FORMING

Copper was mixed with the refractory metal chromium in order to produce the material from which the spray formed electrodes were made. An optical micrograph taken before welding, as seen in Figure 43, shows a relatively uniform distribution of the chromium throughout the copper. At high magnification, the small, spherical chromium precipitates were measured to be, on average, approximately 2  $\mu\text{m}$  in diameter. There was very little variation observed at different locations within the electrode.



**Figure 43. Spray Formed Electrode, Before Welding (500x)**

The same end result was seen with the spray formed electrodes as with the other bulk processed electrodes. The initial welding degraded the copper until the small chromium precipitates built up to form a protective layer. This layer can be seen in the picture in Figure 44. The layer was not as well defined as it was for the powder blended case, therefore it was not as effective as a shield, and the test results support the theory that there was not quite as much protection provided. The material loss was reflective once again of a conditioning phase for the electrode. Overall, the spray formed electrode lost

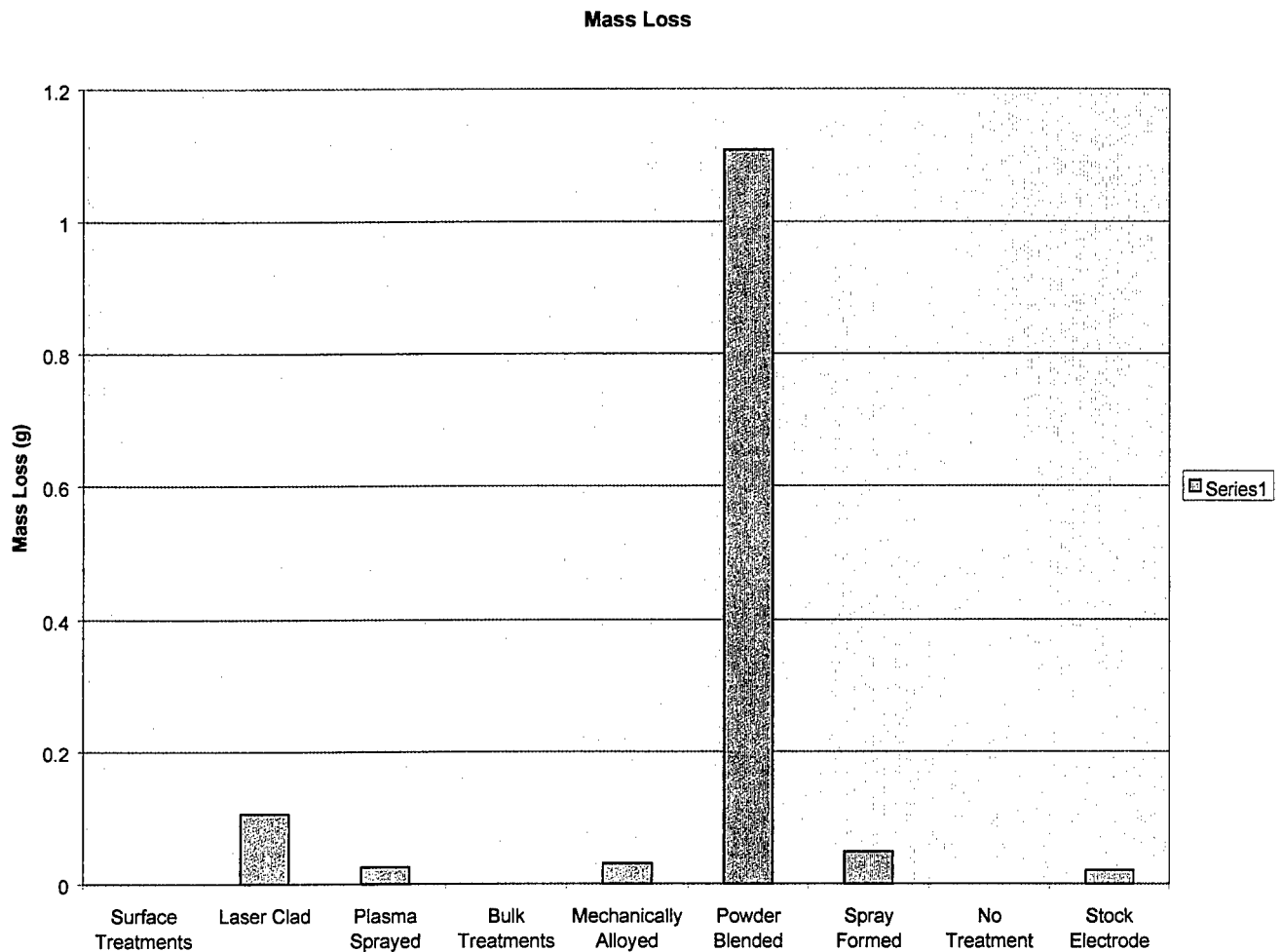


**Figure 44. Spray Formed Electrode, After Welding (500x)**

48.32 mg and 0.343 mm. The weld quality was very good, however, with an average nugget size of 4.521 mm and a 90 percent good weld rate. These results are compared to those for other electrodes in Table 4.

### 5.3 PROCESSING TECHNIQUE COMPARISON

A comparison of the various electrode processing techniques revealed that bulk techniques far out performed surface treatments. The bulk processed batch still exhibited considerable mass and length loss, however. This is explained by the snowball analogy



**Figure 45. Mass Loss Comparison**

discussed previously. Although material loss is significant, there is a conditioning phase required in which the electrode builds up a refractory metal shield against eutectic degradation. The mass loss is graphed in Figure 45.



Mass loss was the most significant in the powder blended electrode. For all the others, it was comparable. The electrodes cannot be evaluated on material loss alone, however. Table 4 shows a comparison of the weld quality resulting from each technique.

	Ave Size	Mass Loss (g)	Bad Welds	Good Welds	% Good
Mechanically Alloyed	172.78	0.0495	8	32	80
Powder Blended	178.60	2.1832	3	37	92.5
Spray Formed	177.98	0.0650	4	36	90
Plasma Sprayed	26.45	0.0400	35	5	12.5
Laser Clad	168.00	0.1488	14	26	65
Stock	136.68	0.0353	8	32	80

Table 4. Quantitative Test Results

In Table 4, it is clear that the material loss was not necessarily a prediction of weld quality. Again, the bulk processing techniques performed much better overall than the surface techniques. The best processing technique as qualified by weld quality and material loss comparison was the spray formation. The mass loss was just 0.048 mg and the good weld rate was 90 percent. In terms of weld rate alone, the powder blended electrodes performed the best with a rate of 92.5, percent although mass loss was significant.

Coating techniques were not successful in improving weld performance. In all cases, applied coatings degraded rapidly and did not provide the necessary protection in suppressing eutectic formation.

## 6.0 CONCLUSIONS

The results of this project supported the current belief that copper-aluminum eutectic formation contributes to the degradation of traditional copper electrodes used for aluminum resistance welding. Evidence of the eutectic was found as early as the 22<sup>nd</sup> weld when using a conventional electrode. This is relatively early in the electrode's average lifetime of a few hundred spots. Electrodes were fabricated from copper with refractory metal additions to evaluate alloy modification as a means to suppress eutectic formation and improve electrode performance. The fact that evidence of eutectic formation was not found on the sampled welds made with these electrodes does not allow the conclusion that eutectic formation has been eliminated, but it does indicate that it has been suppressed.

Results of this research suggest that it is possible to make improvements to standard electrodes. The stock electrode performance as measured by weld quality was matched by one of the bulk processed techniques evaluated and surpassed by the other two. There are many parameters that can be changed during the surface processing steps, but it is not likely that a coating applied to the surface will result in the required protection. This is the case because the coatings applied to the surface have to withstand extreme weld conditions that make a strong, lasting bond nearly an impossibility. Therefore, improvements in electrode lifetime are likely to be made by using a bulk processing method rather than a surface technique.

Since the goal is to develop an electrode processing technique that will be suitable for mass production, any unnecessary steps should be eliminated. These test results indicate that there is not an advantage to mechanically alloying the powders used for bulk

processing before final fabrication. Since that step involves an extra commitment of time and resources, it is undesirable for mass production.

In general, alloy modifications via the addition of a refractory element will enhance the performance of the copper electrodes used in resistance welding of aluminum. By the optimization of processing parameters, the benefits of alloy addition through each processing technique can be maximized and the degradation of electrodes minimized, resulting in a processed electrode that has a greater lifetime and is more suitable to resistance welding aluminum than current electrodes.

## 7.0 RECOMMENDATIONS

If more time and resources were available, the first recommendation would be to proceed with further testing of the bulk processed electrodes. To assure an equitable comparison of processing techniques, the same alloying element and amount of alloying element should be used in each case. After a particular processing method is selected, emphasis should be placed on developing the processing parameters for that technique to produce the best refractory distribution. In addition, the most appropriate welding parameters should be defined for all potential applications.

If the electrodes are going to be used commercially, research into the cost of mass production should be completed. Although expensive on a small scale, various processing techniques may become more cost effective as larger numbers of electrodes are produced. In addition, if emphasis were placed on one type of electrode to be produced on a large scale, facilities and processes could be tailored to specific applications.

Another concern for gauging electrode performance is conductivity. Due to the limited availability of materials, conductivity tests could not be performed in this effort. This is however, an important aspect of a resistance welding electrode and should be given its due consideration. Different processing techniques may prove to produce an electrode that provides a higher quality weld and lasts longer at different current levels, but requires more energy to operate. Again, this is a cost issue for the Navy or commercial industry to consider. The more energy required to create a good weld, the more cost associated with production. This and other economic issues should be evaluated.

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